

## Advancing the integration of spatial data to map human and natural drivers on coral reefs

Wedding, Lisa; Lecky, Joey; Gove, Jamison; Walecka, Hilary; Donovan, Mary; Williams, Gareth; Jouffray, Jean-Baptiste; Crowder, Larry; Erickson, Ashley; Falinski, Kim; Friedlander, Alan; Kappel, Carrie; Kittinger, John; McCoy, Kaylyn; Norstrom, Albert; Nystrom, Magnus; Oleson, Kirsten; Stamoulis, Kostantinos; White, Crow; Selkoe, Kimberly

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RESEARCH ARTICLE

# Advancing the integration of spatial data to map human and natural drivers on coral reefs

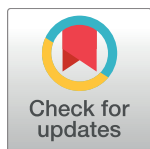
Lisa M. Wedding<sup>1☯\*</sup>, Joey Lecky<sup>2,3☯</sup>, Jamison M. Gove<sup>3‡</sup>, Hilary R. Walecka<sup>1,4‡</sup>, Mary K. Donovan<sup>5‡</sup>, Gareth J. Williams<sup>6‡</sup>, Jean-Baptiste Jouffray<sup>7‡</sup>, Larry B. Crowder<sup>1</sup>, Ashley Erickson<sup>1</sup>, Kim Falinski<sup>2</sup>, Alan M. Friedlander<sup>5,8</sup>, Carrie V. Kappel<sup>9</sup>, John N. Kittinger<sup>10,11</sup>, Kaylyn McCoy<sup>5</sup>, Albert Norström<sup>7,12</sup>, Magnus Nyström<sup>7,12</sup>, Kirsten L. Oleson<sup>2</sup>, Kostantinos A. Stamoulis<sup>5,13</sup>, Crow White<sup>14</sup>, Kimberly A. Selkoe<sup>9,4,15</sup>

**1** Center for Ocean Solutions, Stanford University, Palo Alto, California, United States of America, **2** Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, Honolulu, Hawai'i, United States of America, **3** Ecosystem Sciences Division, NOAA Pacific Islands Fisheries Science Center, Honolulu, Hawai'i, United States of America, **4** Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, California, United States of America, **5** Fisheries Ecology Research Lab, Department of Biology, University of Hawai'i at Mānoa, Honolulu, Hawai'i, United States of America, **6** School of Ocean Sciences, Bangor University, Anglesey, United Kingdom, **7** Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden, **8** Pristine Seas, National Geographic Society, Washington, DC, United States of America, **9** National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, Santa Barbara, California, United States of America, **10** Conservation International, Center for Oceans, Honolulu, Hawai'i, United States of America, **11** Arizona State University, Center for Biodiversity Outcomes, Julie Ann Wrigley Global Institute of Sustainability, Tempe, Arizona, United States of America, **12** Global Economic Dynamics and the Biosphere Academy Programme, Royal Swedish Academy of Sciences, Stockholm, Sweden, **13** Curtin University, Department of Environment and Agriculture, Perth, Australia, **14** Biological Sciences Department, California Polytechnic State University, San Luis Obispo, California, United States of America, **15** Hawai'i Institute of Marine Biology, University of Hawai'i at Mānoa, Kāne'ohe, Hawai'i, United States of America

☯ These authors contributed equally to this work.

‡ These authors also contributed equally to this work.

\* [lwedding@stanford.edu](mailto:lwedding@stanford.edu)



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## Abstract

A major challenge for coral reef conservation and management is understanding how a wide range of interacting human and natural drivers cumulatively impact and shape these ecosystems. Despite the importance of understanding these interactions, a methodological framework to synthesize spatially explicit data of such drivers is lacking. To fill this gap, we established a transferable data synthesis methodology to integrate spatial data on environmental and anthropogenic drivers of coral reefs, and applied this methodology to a case study location—the Main Hawaiian Islands (MHI). Environmental drivers were derived from time series (2002–2013) of climatological ranges and anomalies of remotely sensed sea surface temperature, chlorophyll-a, irradiance, and wave power. Anthropogenic drivers were characterized using empirically derived and modeled datasets of spatial fisheries catch, sedimentation, nutrient input, new development, habitat modification, and invasive species. Within our case study system, resulting driver maps showed high spatial heterogeneity across the MHI, with anthropogenic drivers generally greatest and most widespread on O'ahu, where 70% of the state's population resides, while sedimentation and nutrients were dominant in less populated islands. Together, the spatial integration of environmental and anthropogenic driver data described here provides a first-ever synthetic approach to

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visualize how the drivers of coral reef state vary in space and demonstrates a methodological framework for implementation of this approach in other regions of the world. By quantifying and synthesizing spatial drivers of change on coral reefs, we provide an avenue for further research to understand how drivers determine reef diversity and resilience, which can ultimately inform policies to protect coral reefs.

## Introduction

Understanding the drivers that cause changes in coral reef ecosystems is essential to designing management interventions that enhance positive outcomes and minimize negative impacts. While coral reef ecosystem structure and function vary naturally due to changes in environmental drivers [1–2], anthropogenic drivers are increasingly becoming the primary structuring forces of coral reef condition [3–5]. Many of these anthropogenic drivers have the potential to not only influence individual populations or ecological processes, but can also erode coral reef ecosystem resilience [6–10]. Accumulated evidence shows that coral reefs can shift from coral dominated to other undesirable alternative ecosystem states as a result of chronic human impacts [11–15]. Such reorganization of ecosystem structure and function may be difficult to reverse and may lead to loss of ecosystem services [16–19].

Disentangling the interacting effects of environmental and anthropogenic drivers across space and time requires coordinated quantification of a broad array of data over large spatio-temporal scales and the adoption of a macro-ecological approach to their analysis. In the absence of such comprehensive datasets, past efforts have been highly skewed towards environmental drivers, while anthropogenic impacts often are quantified by coarse proxies, such as human population density [20]. Such proxies often confound and conflate the effect of interacting individual drivers [15,4,21–22], and provide little predictive power at the relevant scales that decision-makers require to make difficult choices about how to apply limited resources to reduce local threats to coral reef health in the face of a rapidly changing ocean [23–24]. Emerging technology and data streams (e.g., global observing systems, citizen-science, and shared data repositories) increasingly allow for compiling and analyzing large data sets on both anthropogenic and environmental drivers over a broad range of scales, offering an unprecedented opportunity to study and understand ecosystem dynamics and swiftly inform management decisions. Big data refers broadly to the integration and communication of information in novel ways to produce valuable scientific insights about the world [25–26]. Such big data approaches have been harnessed to map drivers of ecosystem change and quantify spatial and temporal changes in cumulative impacts on the oceans at a global scale [5,27], and are increasingly being used to synthesize spatial data to determine drivers of coral reef ecosystem state [28–29]. Building on these past efforts, the overall goal of this study was to build a methodological approach to guide the synthesis and mapping of large spatio-temporal data sets, addressing critical issues of scale, data interoperability, and management relevance.

Ensuring actionable science and increased management uptake of scientific findings requires a comprehensive methodological framework for spatial data synthesis that engages managers from the initial phase in the driver identification, synthesis, and distillation process [30]. This study advances a methodological approach for guiding the synthesis and mapping of large spatio-temporal data sets to support coral reef ecosystem studies and management decision-making. Our first objective was to establish a methodological approach to support the spatial integration of data to map drivers on coral reef ecosystems. The methodological

framework developed in this study involved four main steps: 1) development of a driver typology and approach for identifying management end-user needs, 2) establishment of the temporal and spatial scale(s) of analyses, 3) quantification and mapping of drivers, and 4) distilling and communicating driver data sets to managers and policymakers. Our second objective was to apply this methodological approach in a case study by quantifying and mapping environmental and anthropogenic drivers of coral reef ecosystem states in Hawai'i. The case study site was chosen due to the geographic variability of impact gradients and coral reef ecosystem shifts documented on Hawaiian coral reefs [31–34]. This case study allowed us to establish and operationalize a methodological approach to spatially integrate data sets on coral reefs that can be applied to future studies in order to inform pressing problems facing coral reefs worldwide.

## Materials and methods

### Study area

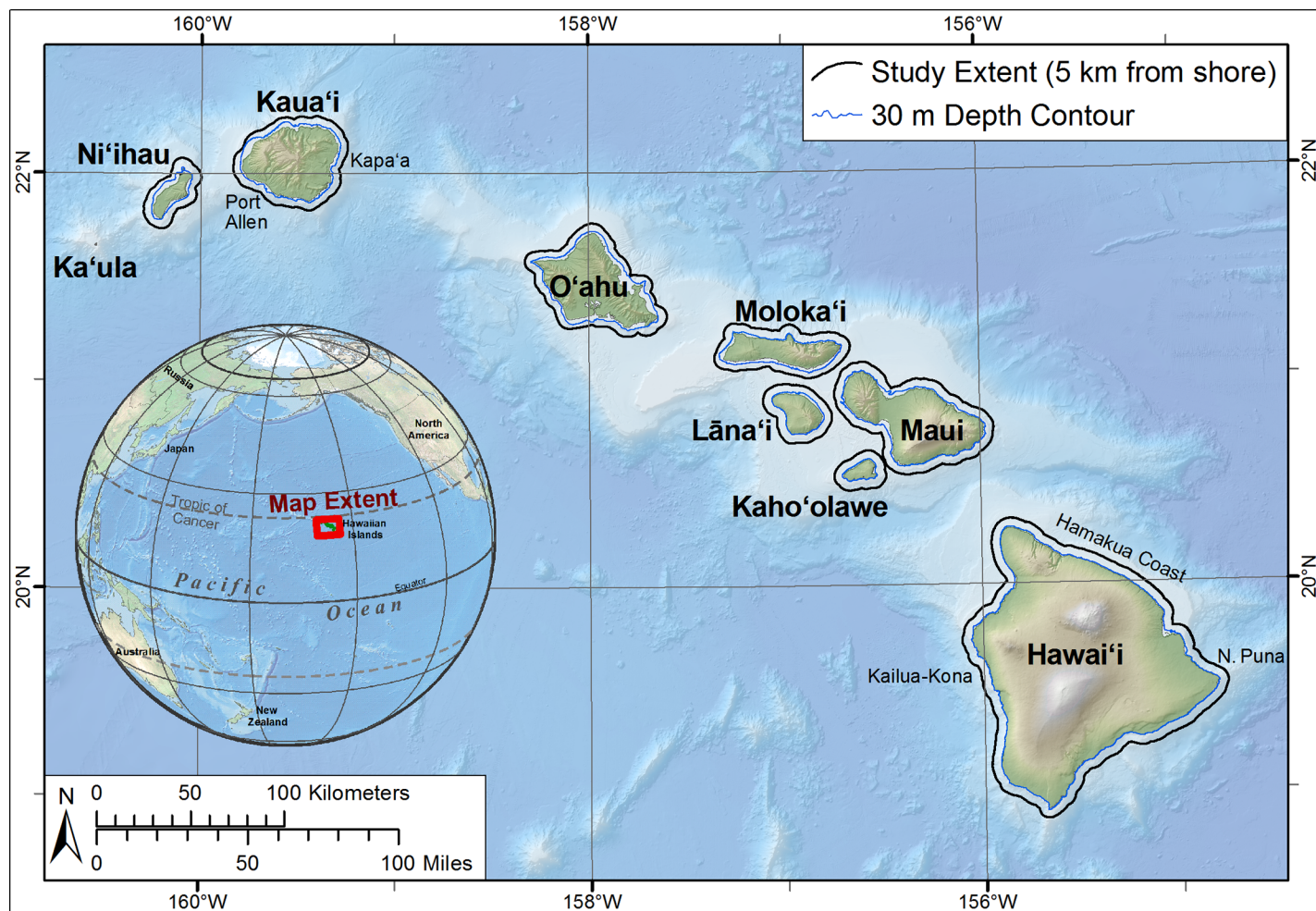
The main Hawaiian Islands (MHI) consist of eight high volcanic islands. The archipelago's isolation in the middle of the Pacific Ocean exposes reefs there to large open ocean swells and strong trade winds, which strongly influence the structure of the coral reefs. These dynamic natural processes and extreme isolation have sculpted distinctive marine communities, with 25% endemism, that play a valuable role as a global biodiversity resource [35–38]. Some of these endemics are dominant components of the coral reef community with extremely high conservation value [39–40]. In Hawai'i, coral reef ecosystems play an important role in the culture, lifestyle, and economy, providing nearly \$360 million annually in benefits to society [41,31].

The study area encompassed all nearshore waters of the MHI from shore to 5 km offshore (Fig 1). Coral reefs have been in decline in Hawai'i over the past 100 years due to the intense human pressure from a variety of overlapping uses such as recreational and commercial fishing, developed shorelines and watersheds, expanding ranges of invasive species, pollution, and other effects of an immense and growing coastal population and tourism industry [42,32,43]. The study area was chosen as a case study system because it contains gradients of environmental drivers, encompasses a broad range of human activities related to coral reefs, and prior to this study lacked sufficient synthesized data at spatial and temporal scales necessary to support ecosystem-based management of Hawaiian coral reefs.

### Methodological framework for spatial data integration

The methodological framework developed in this study involved four main steps to support the spatial data integration to map drivers on coral reefs across space and time (Fig 2). Our aim was to tackle the challenges of quantifying human uses and influences that have been poorly measured and/or difficult to access at fine spatial scales in the past. We synthesized numerous existing spatial data sets related to anthropogenic drivers and filled data gaps by developing models and specialized proxies to represent specific anthropogenic drivers, including fisheries catch from commercial and non-commercial fisheries (line, net, and spear gear types), land-based stressors (nutrients, sedimentation, new development), invasive species (fish and algae), and habitat modification. The typology of drivers created in step 1 was based on the key anthropogenic and environmental drivers identified by scientists, managers and key stakeholders in the study area (Fig 3). For instance, managers from the NOAA Office of National Marine Sanctuaries and State of Hawai'i Division of Aquatic Resources (DAR) were engaged before the research started in order to provide input on the framing of the project and identify key drivers to include in the typology that they estimated to be most impactful on coral reefs. The typology expanded on a social-ecological framework that identified the





**Fig 1. Study area.** Map highlighting the main Hawaiian Islands study area and spatial footprint of anthropogenic and environmental driver data developed for this study extending offshore to 5 km. Biological monitoring data on coral reefs is generally shallower than the 30 m depth contour.

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primary human impacts that mediate the condition of coral reef ecosystems by Kittinger et al. [44] and integrated key environmental drivers that were identified by Gove et al. [45]. Specifically, we included environmental forcings known to be major drivers of coral reef ecosystem state, namely sea surface temperature (SST), chlorophyll-*a* (a proxy for phytoplankton biomass), irradiance, and wave power [4].

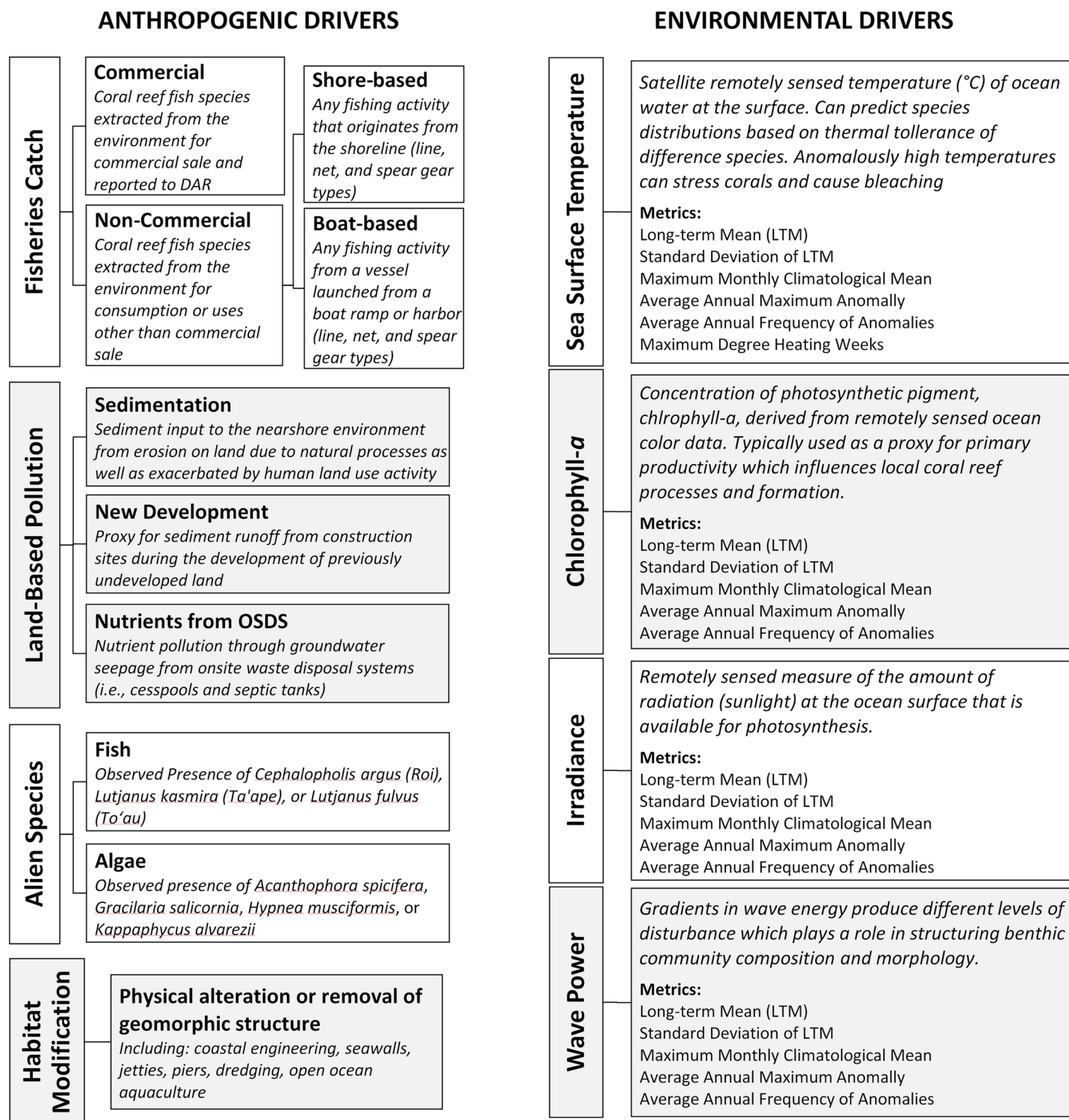
The second step involved the development of appropriate scaling (geographic extent, temporal, and spatial resolution) to inform the data synthesis based on coral reef management information needs at the state level (Table 1). In Hawai'i, as in many coral reefs globally, the ocean is managed at multiple scales (state-wide, regionally, and locally). Accordingly, the scale and geographic extent of the data synthesis and integration were guided by the planned management application and utility of these data within the constraints of native spatial resolutions of input data. The spatial scale in relation to grain size (pixel size) of the data sets were defined by each data source. The finest grain size was created for each data source in order to provide managers with the highest resolution data possible. Recommendations from the managers guided the geographic extent of the data. For a majority of the data sets, the temporal scale represented approximately a ten-year average, which provided managers with a data set that gave



**Fig 2. Methodological framework.** Overall approach and steps to support the integration of spatial data to map human and natural drivers on coral reefs.

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a broader temporal understanding of drivers across space instead of a single snapshot in time. Our goal was to create driver data sets at the finest spatial scale possible that supports



**Fig 3. Anthropogenic and environmental drivers.** Typology for primary proximate anthropogenic and environmental drivers for coastal waters of the main Hawaiian Islands from the shoreline extending 5 km offshore.

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management information needs and this step was carried out with federal and state-level coral reef managers.



**Table 1. Anthropogenic and environmental drivers mapped and input data sources.**

Anthropogenic Drivers	Units	Spatial resolution	Temporal range	Data Source
Fisheries Catch—Commercial	annual average catch in kg/ha by gear (line, net, and spear)	100 m	2003–2013	Reported Commercial Catch 2003–2013 (DAR); Commercial Reporting Blocks (OP)
Fisheries Catch -Non-Commercial (Shore-Based)	annual average catch in kg/ha by gear (line, net, and spear)	100 m	2004–2013	Island-scale estimates of catch (kg/yr by gear) from MRIP 2004–2013 [50]; USGS DEM (slope); TIGER Roads; HMRG Bathymetry Synthesis
Fisheries Catch -Non-Commercial (Boat-Based)	annual average catch in kg/ha by gear (line, net, and spear)	100 m	2004–2013	Island-scale estimates of catch (kg/yr by gear) from MRIP 2004–2013 [50]; Boating Facility locations (OP); Human population (US Census, 2010)
Sedimentation	average annual amount of sediment (tons/yr)	100 m	2005	InVEST Sediment Delivery Ratio Model output [57]; National Hydrography Dataset
New Development	relative level of new development	100 m	2005–2011	NOAA C-CAP 2005–2010/11; NHD Watersheds; Distance from shore
Nutrients from OSDS	g/day and effluent in gallons/day	500 m	2009–2014	OSDS Point location and estimated effluent/nutrient flux [61–62]
Invasive Species	Presence only of invasive fish and algae	500 m	2000–2013	Hawaii Monitoring and Research Collaborative Database (2000–2013); Invasive marine algae surveys [64]
Habitat Modification	presence of habitat modifying features	500 m	2001–2013	NOAA CCMA Habitat Maps (2007); NOAA ESI lines (2001); Maintained Channels (2013); Offshore Aquaculture point locations
Oceanographic Drivers	Units	Spatial resolution	Temporal range	Data Source
Sea Surface Temperature	° Celsius	5 km	2000–2013	NOAA Pathfinder, NOAA/NESDIS/STAR Blended SST 0.1 and 0.05 degree (weekly composites)
Chlorophyll-a	mg/m <sup>3</sup>	4 km	2002–2013	MODIS (8-day composites)
Irradiance	Einstein m <sup>-2</sup> d <sup>-1</sup>	4 km	2002–2013	MODIS (8-day composites)
Wave Power	KW/m	0.5–1 km	2000–2013	Simulating Waves Nearshore (SWAN) model—(hourly)

Input data sets used to develop continuous spatial layers of anthropogenic and environmental drivers for coastal waters of the Main Hawaiian Islands from the shoreline extending 5 km offshore. The following climatological metrics were calculated for each environmental driver: long-term mean, standard deviation of long-term mean, climatological maximum, average annual maximum anomaly, frequency of anomalies, and for SST only: maximum degree heating weeks. Acronyms: DAR—Hawai‘i Division of Aquatic Resources; OP—Hawai‘i Office of Planning; MRIP—Marine Recreational Information Program; USGS—United States Geological Survey; DEM—Digital Elevation Model; InVEST—Integrated Valuation of Ecosystem Services and Tradeoffs; NHD—National Hydrography Dataset; OSDS—On Site waste Disposal Systems; NOAA—National Oceanic and Atmospheric Administration; CCMA—Center for Coastal Monitoring and Assessment; ESI—Environmental Sensitivity Index; C-CAP—Coastal Change Analysis Program; TIGER—Topologically Integrated Geographic Encoding and Referencing; HMRG—Hawai‘i Mapping Research Group; NESDIS STAR—National Environmental Satellite, Data, and Information Service, Center for Satellite Applications and Research; SST—Sea Surface Temperature; MODIS—Moderate Resolution Imaging Spectroradiometer

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The third step involved the quantification of anthropogenic and environmental drivers that are known from the literature to be major drivers of coral reef ecosystem state. We extended the island-scale modeled and satellite-based metrics of environmental drivers developed by Gove et al. [45] to intra-island spatial scales. In addition, we created maps of anthropogenic drivers that have been poorly measured and/or difficult to access at this scale in the past (e.g., fisheries catch, sedimentation, nutrients) and synthesized current data sets on habitat modification and invasive species. During this step, the project team met with state and federal management staff to receive feedback on the proposed methodology and to vet the driver data sets. The final key step in the process involved distilling, communicating, and serving these datasets to ensure their use in future research, so as to broaden our understanding of the coral reef ecosystem state and inform best ecosystem-based management practices.

## Anthropogenic driver data and spatial analysis

**Fisheries catch.** Nearshore wild-capture food fisheries in Hawai'i consist of diverse groups of fishers using a wide array of gears and targeting hundreds of species [46–48]. Over-fishing can cause ecosystem degradation and long-term economic loss. Fine-scale information on catch and effort for Hawaiian nearshore fisheries is virtually nonexistent. Commercial catch of reef fishes is reported to the State of Hawai'i DAR based on large reporting blocks; furthermore, it constitutes a very small proportion of all reef fishes caught and is unrepresentative of nearshore fisheries as a whole [49–50]. McCoy [50] examined 10 years of data from the NOAA Marine Recreational Information Program (MRIP) and other data sources, including creel (angler) survey data, to estimate non-commercial nearshore catch by gear type and platform (boat- or shore-based) for each island and found this catch to be, on average, 10 times greater than the reported commercial catch.

To map the average annual catch of reef fishes for the MHI, we combined commercial reported catch with island-level estimates of non-commercial catch from McCoy [50], along with an index of accessibility for shore- and boat-based fishing. We created nine separate data layers for fishing, grouped into three categories: 1) commercial fishing, 2) non-commercial shore-based fishing, and 3) non-commercial boat-based fishing, each with three gear classes: line, net, and spear fishing. We excluded invertebrates and coastal pelagic finfishes (e.g., *Selar crumophthalmus* and *Decapterus* spp.) from the fisheries data layers since these taxa were either loosely reef-associated or were poorly represented in the biological datasets. Each final data layer represented an annual average catch in kg/ha, at 100 m (1 ha) spatial resolution.

For **commercial fishing**, we calculated the average annual catch of reef fishes by gear category (line, net, and spear) over the years 2003–2013 as reported in commercial catch data by large irregular reporting blocks (50–250 km<sup>2</sup>), collected by State of Hawai'i DAR Commercial Marine Landings Database (CML). The gear types reported in the CML database do not distinguish boat- from shore-based gears.

For **non-commercial fishing**, we used estimates from McCoy [50] of average annual catch by platform (boat, shore) and gear type at the island scale, from 2004–2013 derived from MRIP combined fisher intercept and phone survey data [50]. To spatially distribute these island-scale estimates of catch offshore around each island, we developed and used spatial proxies for accessibility to fishers. For **shore-based non-commercial fishing**, we combined two different measures of shoreline accessibility (terrain steepness and presence of roads) to define a total of nine accessibility categories which were then weighted with respect to fisheries catch based on expert opinion (see [S2 Supplement](#) for detailed methodology and weighting factors). For **boat-based non-commercial fishing**, we combined over-water distance to boat harbors and launch ramps with a Gaussian decay function that assumed the majority of catch occurs within 15–20 km of each harbor, and weighted the amount of catch out of each ramp/harbor by the human population within 30 km of the harbor or ramp (See [S2 Supplement](#) for details). Spatial analyses were run separately for each boat harbor or launch ramp (so that footprints from nearby harbors could overlap), and then catch surfaces for each harbor/ramp were summed. The decay functions, distances, and weighting factors used to derive non-commercial fishing layers were vetted with resource experts and managers in absence of empirically based values.

For each of the 9 fishing layers described above, marine protected area boundaries and military restricted areas were used to adjust catch according to specific restrictions in each area. We conducted a comprehensive review of existing state and federal regulations in order to update military restricted areas and outdated marine managed area boundary data for the State of Hawai'i, and then evaluated each area with regard to the 9 fishing categories mapped.

Fish catch incomplete no-take MPAs was set to zero and reduced in other areas with restricted access according to expert input and local knowledge. The final units for each layer were converted to average annual catch in kg/ha, so that the scale was consistent across layers and could be summed across different combinations of gear types and platforms (e.g., total spearfishing catch across all platforms, or total catch from the non-commercial sector only).

Non-commercial fishing maps were validated using estimates of annual catch of reef fishes compiled from existing site-based intercept surveys from creel survey reports (see [S1 Supplement](#) for creel survey references). Creel surveys estimate catch and effort in a particular area using a sampling program that involves fisher interviews and inspection of catch. Survey areas described or mapped in creel survey reports were digitized and used to sum catch for the corresponding areas from the total non-commercial catch map. A least-squares linear regression with intercept anchored at the origin was performed to compare the two sets of estimates and compared to the 1:1 line (see [S1 Supplement](#)).

**Land-based stressors.** Sediment from various land-based stressors can affect reef health by smothering corals and blocking light, leading to degradation of reef ecosystems [51]. In addition, excess nutrients can trigger macroalgal blooms that smother and kill corals [52–53]. In order to map land-based stressors, we developed tailored models of nutrient and sediment impacts to reefs by combining estimates of loads with ecologically informed models of their spatial distribution into the nearshore. To quantify sedimentation, we used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) sediment delivery ratio model [54–55] to estimate sediment delivery for each of the eight MHI [56]. The model was customized and parameterized for Hawai‘i, and calibrated using scientific data on sediment loads [57]. The model predicted average annual sediment export (tons/yr) from each terrestrial map pixel as a function of vegetation cover characteristics, geologic substrate, soil erodibility, rainfall erosivity, and slope. The resulting modeled sediment loads were aggregated by drainage basin to each point where a stream meets the coast and then dispersed offshore using the Kernel Density tool in ArcGIS, resulting in a map of sediment plumes 1.5 km offshore with 100 m cell size. The Density tool was run iteratively for each pour point, land area was clipped out, and offshore values were back-calculated to sum to the input sediment load. Finally, each individual plume raster was added together with Cell Statistics (See [S1 Supplement](#) for details).

The InVEST Sediment Delivery Ratio model was based on static land use land cover data and as a result, sources of sediment not captured in this model included new construction sites that strip land of vegetation, leaving bare soil s vulnerable to erosion, and often harbor additional large piles of soil on site for grading and landscaping. To capture this source of land-based pollution, we identified areas that had been newly developed over a recent five-year period using high resolution data from NOAA’s C-CAP (Coastal Change Analysis Program). We identified all map pixels that changed from undeveloped land to a hard, man-made surface from 2005 to 2010, and calculated the area of new development per watershed. We used a Gaussian function that decays with distance from shore (similar to that used by the ArcGIS Kernel Density tool for the sediment layer) to disperse these watershed-scale values offshore and approximate the dispersal of sediment from new construction into the nearshore environment. Values were re-scaled from 0 to 1 in order to represent the relative level of new development with the final layer having 100 m cell sizes.

Hawai‘i has the highest number of onsite waste disposal systems (OSDS) (i.e. cesspools and septic tanks) per capita in the U.S., many of which are adjacent to the coastline (EPA—<https://www.epa.gov/uic/cesspools-hawaii>). These OSDS leach excess nutrients and pollutants into groundwater that flows to the ocean [58]. Excess nutrients can promote rapid algal growth, outcompeting corals and disrupting the ecosystem [59–60]. To represent this impact spatially, we used data on OSDS in the form of point data from the University of Hawai‘i and Hawai‘i



Department of Health [61–62]. Data consisted of estimated nitrogen flux and phosphorous flux from each Tax Map Key parcel with OSDS in units of kg/day and effluent in gallons (3.8 L) per day. We converted the points to a raster by summing nutrient flux values within 500 m x 500 m pixels. Focal statistics were used to calculate the total flux within a 1.5 km radius of each cell based on sediment plume extents measured by Ostrander et al. [63]. We produced three final layers at a cell size of 500 m: nitrogen, phosphorus, and total effluent flux within 1.5 km of each map pixel with final units of g/day/7 km<sup>2</sup> for nutrients and gal/day/7 km<sup>2</sup> for effluent (7 km<sup>2</sup>  $\approx$  area of a circle with 1.5 km radius).

**Invasive species.** Several species of alien algae have become invasive in Hawai'i (e.g., *Acanthophora spicifera*, *Gracilaria salicornia*) [64]. Likewise, several fish species have become invasive following intentional introductions as food fish in the 1950s [65]. Two data layers were created to characterize the presence of invasive fishes and invasive algal species in near-shore waters of the MHI. The invasive algae data were from surveys conducted in 2002 and data from the Hawaii Monitoring and Research Collaborative, which synthesized underwater visual surveys from multiple sources on fishes and benthic assemblages over the years 2000–2013 [66–67]. Transects were categorized with presence of invasive fish species (*Cephalopholis argus*, *Lutjanus kasmira*, *Lutjanus fulvus*) and invasive algae species (*Acanthophora spicifera*, *Gracilaria salicornia*, *Hypnea musciformis*, *Kappaphycus alvarezii*) and these point data were converted to raster. To account for uncertainty in geographic position, and movement of the fish species or fragmentation and spread of algae, focal statistics were run to calculate presence within a 1 km radius of invasive algae observations and a 2 km radius of invasive fish observations. A 2 km buffer was used for fishes based on literature about the home ranges of *C. argus* and *L. kasmira* [68–69] and a 1 km scale was used for invasive algae based on Smith et al. [70]. The layers represent the presence only of invasive fishes and algae, with a cell size of 500 m.

**Habitat modification.** Coastal habitats are under increasing pressure and use from anthropogenic activities. Here we defined habitat modification as the alteration, or removal of geomorphic structure, as a result of human use. We mapped the presence of habitat modifying features like seawalls, piers, breakwaters, dredged areas, artificial land (i.e. filled wetlands), and offshore structures by combining several existing datasets derived primarily from satellite and aerial imagery. We integrated the following data sets into the habitat modification layer: 1) artificial shoreline, 2) maintained channels and dredged areas, and 3) offshore aquaculture. The layer represents the presence or absence of habitat modification, with a cell size of 500 m.

## Environmental driver data and spatial analysis

Proper characterization of environmental drivers through space and time is critical to understanding the intrinsic biophysical interactions occurring within coral reef ecosystems. Here, we built upon previous work by Gove et al. [45] and developed a suite of metrics for four environmental drivers of coral reefs (sea surface temperature, Chlorophyll- *a*, irradiance, and wave power) at 0.5–4 km spatial resolution across the MHI.

Sea surface temperature (SST) plays an important role in a number of ecological processes occurring within coral reef environments and can vary in response to diel, intra-seasonal (e.g. mesoscale eddies), seasonal, inter-annual (e.g. El Nino Southern Oscillation) and decadal (e.g. Pacific Decadal Oscillation) forcing. SST (°C) was quantified weekly at 5 km from multiple satellite-derived data sets, including NOAA's Pathfinder v5.2 and NOAA's Center for Satellite Applications and Research blended 11 km and 5 km daily data set, available from 1985–2013. A bias adjustment was applied, derived from linear regression to the overlap periods of data-sets. Data were excluded if deemed of poor quality (quality value < 4, [71]) or if individual pixels were masked as land (see S1 Supplement for more detail).

Chlorophyll-*a* is a widely used proxy for phytoplankton biomass (e.g., Gove et al. [72]) and as an indicator for changes in phytoplankton production (e.g., Chassot et al. [73]), an essential source of energy in the marine environment [74]. Irradiance represents the amount of solar radiation (sunlight) at the ocean surface that is available for photosynthesis. Chlorophyll-*a* ( $\text{mg}/\text{m}^3$ ) and irradiance ( $\text{Einstein}/\text{m}^2/\text{d}$ ) were obtained from NASA's 4 km, 8 day, Moderate Resolution Imaging Spectroradiometer (MODIS; <http://oceancolor.gsfc.nasa.gov/cms/>) data set available from July 2002 to present. Following Gove et al. [45], a multistep masking routine was applied to remove spurious data associated with optically shallow waters ( $< 30$  m) and errors induced by terrigenous input, re-suspended material, or bottom substrate properties [75] (see [S1 Supplement](#) for more detail).

Gradients in wave forcing result in varying levels of disturbance underwater that have strong implications for both benthic and fish communities in coral reefs [2,76]. Wave power ( $\text{kW}/\text{m}$ ), which incorporates both wave period and wave height and therefore represents a more realistic estimate of wave-induced stress on coral reefs, was obtained using University of Hawai'i SWAN (Simulating WAVes Nearshore) wave model, available at 1 hr, 0.5 km resolution from 1979–2013 [77]. Daily maximum wave power was calculated from the hourly data set. Spatial mismatch between model resolution and the high degree of wave refraction, amplification, and dissipation resulted in spurious wave power values in close proximity to shore. As such, all model pixels adjacent to shore ( $\leq 500$  m) were removed prior to analysis (see [S1 Supplement](#) for more detail).

We quantified a suite of metrics in order to effectively capture the ecological relevance of each environmental driver. Monthly climatologies were first calculated utilizing the full time range of data availability. The maximum monthly mean, or the largest value of the 12 monthly climatological values, was selected to represent the upper limit in the 'normal' range of environmental conditions [78–79]. Over time, coral reefs have adapted to exist within a particular climatological range; an envelope of environmental forcings that is region-specific and governed by a reef's geographic location [45]. Anomalous events were then calculated for environmental conditions that exceeded the maximum monthly mean. Specifically, the annual average in the total number and magnitude of anomalous events were quantified for each environmental driver. The long-term mean and standard deviation were also quantified to capture average environmental conditions and the associated time-dependency in those conditions. Finally, the maximum Degree Heating Weeks (DHW;  $^{\circ}\text{C}\text{-weeks}$ ; [www.coralreefwatch.noaa.gov](http://www.coralreefwatch.noaa.gov)), calculated from SST, was also included as a metric of thermal stress on corals [80–81]. Anomaly, climatological maximum, long-term mean, standard deviation and DHW metrics were calculated from 2000–2013. Owing to data availability limitations, metrics for Chlorophyll-*a* and Irradiance were calculated from July 2002–December 2013. For all environmental drivers and metrics, nearshore map pixels with no data were filled with values from the nearest neighboring offshore pixel.

## Driver correlations across islands

We carried out a principle components analysis (PCA) at the island scale to determine which islands share similar sets of dominant drivers in order to help managers gain understanding on the varying needs and priorities for each island based on the extent of dominant drivers. To compare general patterns of anthropogenic and environmental drivers across islands, summary statistics were derived to calculate an island mean for each variable. For each island, a raster mask was created and values within the mask were used to calculate minimum, lower quartile, median, upper quartile, and the maximum, and displayed as boxplots. Median values were then used in a principle components analysis to evaluate correlations among variables

across islands. For environmental drivers, only the climatological maximum metrics were included in the PCA.

## Results

### Spatial patterns of anthropogenic drivers—the Hawaiian Islands as a case study system

**Fisheries catch.** The greatest mapped values of commercial and non-commercial boat-based reef fish catch occurred on the island of O‘ahu, with commercial catch highest off west O‘ahu and the highest non-commercial boat-based catch near Honolulu on the south shore. Across the MHI, catch by the line gear type was at least two times greater than spear or net for non-commercial shore-based fishing, and as much as 10 times greater in the case of shore-based net fishing on Hawai‘i Island. Maui had the highest catch per unit area for shore-based net fishing. Pockets of highly accessible coastline on Hawai‘i Island had the highest total combined catch per unit area in the state (max. value of 40.4 kg/ha on Hawai‘i compared to 29.2 kg/ha on O‘ahu). However, Hawai‘i Island also had large expanses of inaccessible and relatively unfished coastline compared to O‘ahu, which has more reef area and nearly all shorelines are highly accessible, resulting in catch being more widely dispersed. Other areas with exceptionally low catch included the islands of Ni‘ihau and Kaho‘olawe.

On the Kohala Coast of Hawai‘i Island, shore-based non-commercial fishing pressure was relatively high from Kawaihae Bay south to Kiholo Bay, but was more variable and demonstrated localized hotspots of accessibility north of Kawaihae Bay (Fig 4). The inset panels in Fig 4 illustrate how marine protected areas (MPAs) with varying harvest control rules and restrictions on different gear types were accounted for. For example, the Lapakahi MPA has one zone that is fully no take, but allows line and net fishing in the outer zone. The Waialea Bay MPA allows shore-based line fishing throughout the area but prohibits spear or net. Fishery catch maps significantly predicted creel survey data ( $p < 0.005$ ,  $R^2 = 0.64$ ) and the fitted regression line (slope = 0.99) was close to 1:1 (Fig A in S1). In terms of absolute values of average annual catch, the largest differences between our maps and creel surveys results were in Kiholo Bay (which our maps underestimate by 2,700 kg compared to creel results), and waters of Waikiki outside of MPAs (which our maps overestimate by 2,100 kg).

**Land-based stressors.** Mapped outputs of land-based stressors showed highly localized hot spots across the MHI with the greatest values for sedimentation and nutrients occurring in specific locations on Maui, Hawai‘i Island, and the North Shore of O‘ahu. For instance, the highest sediment load across the state occurred at Kaiaka Bay on the north shore of O‘ahu. At the fine-scale, we found that many enclosed embayments or shallow coastal locations with low wave energy were characterized by high levels of sedimentation and nutrients, and often high chlorophyll-*a* values. As an example, Honolua Bay, on the northwest coast of Maui, demonstrated these localized spatial patterns and had regionally high sediment loads for the West Maui watersheds (Fig 5).

New development and on site waste disposal (nutrients—nitrogen and phosphorus flux) had spatial patterns of overlap with the high sediment loads along the coastline surrounding Kaiaka Bay and Hale‘iwa on the north shore of O‘ahu. Across the MHI, the 50 largest single OSDS effluent loads occurred on Maui and Hawai‘i Island. The maximum estimated flux of nutrients into nearshore waters from onsite waste disposal effluent occurred in south Kailua-Kona town on Hawai‘i Island, Kaiaka Bay on O‘ahu, and Kapa‘a on Kaua‘i. Coastal watersheds with the highest amount of new development (i.e. area converted to impervious surfaces) included the south shore of O‘ahu, Kahului and much of central Maui (Fig 5), and the northern Puna district on Hawai‘i Island. Kaua‘i and Maui islands both had high mapped new development and

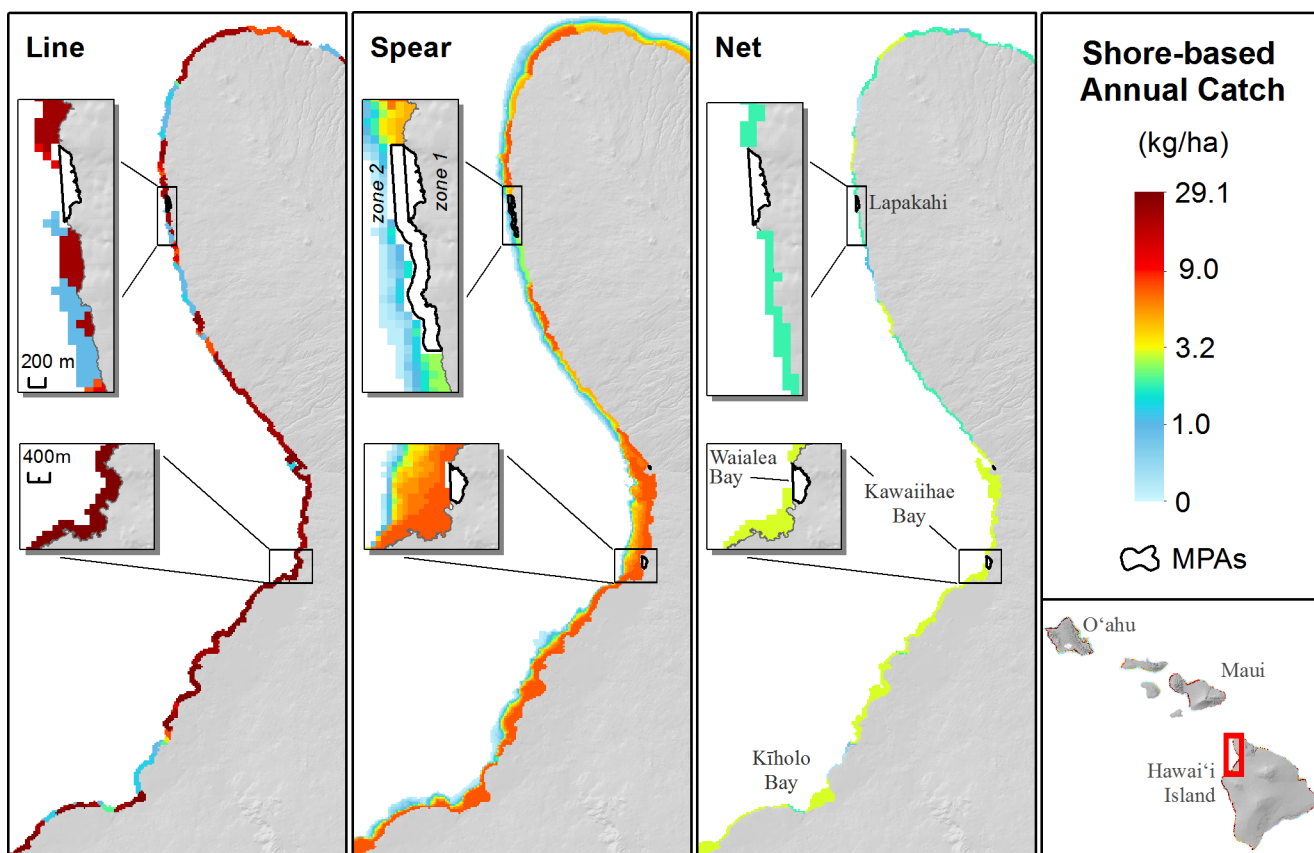
high OSDS nutrient flux combined. For instance, both nutrients from on-site waste disposal and sedimentation were elevated in southwest Kaua'i (e.g., Waimea River near Port Allen).

**Invasive species.** Invasive fish species were present on all islands. On O'ahu, our maps show a majority of the nearshore to be invaded by non-native fishes (Fig 6). Invasive algae species are known to occur in certain discrete locations, particularly Kāne'ohe Bay and Pūpūkea on O'ahu (Fig 6), West Maui, south shore of Moloka'i, and scattered around the other islands.

**Habitat modification.** Habitat modification was abundant at the most populated areas across the MHI such as O'ahu, Hilo on Hawai'i Island, and west Maui. The south shore of Moloka'i also stands out due to numerous remnant native Hawaiian fishpond walls, as well as many dredge scars. The largest areas of continuous habitat modification were on O'ahu from Waikiki to Pearl Harbor, and Kāne'ohe Bay (Fig 6), which have extensively armored and developed shorelines, as well as the largest human populations in the state.

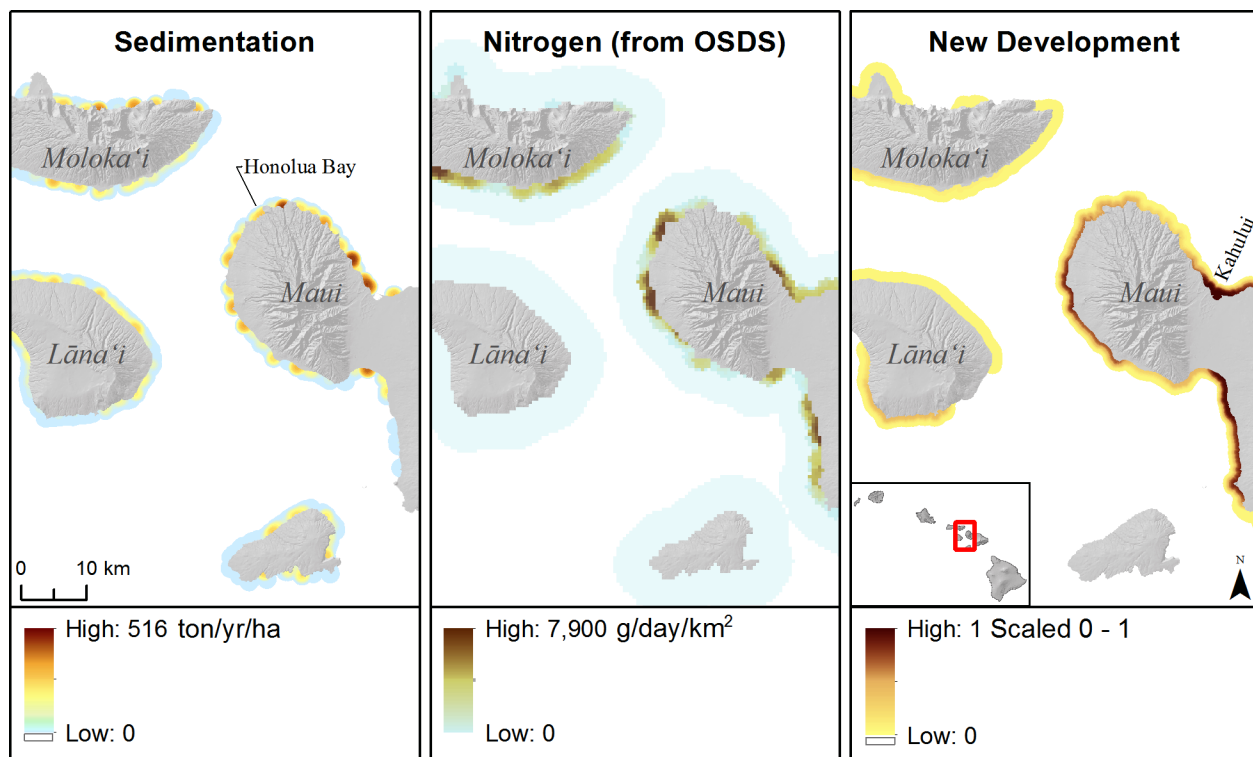
### Spatial patterns of environmental drivers

**Wave forcing.** Hawai'i receives large ocean swell from storms in the northwest Pacific that predominantly impact the northwest facing shorelines of the MHI (Fig 7). However, because of the northwest to southeast orientation of the Archipelago, islands located further northwest (i.e. Ni'ihau, Kaua'i, O'ahu) generally received greater levels of wave forcing and



**Fig 4. Non-commercial shore-based fishing.** Maps of the final continuous spatial layers for non-commercial shore-based fishing catch (kg/ha) on the Kohala coast of the Island of Hawai'i. Maps depict the average annual catch of reef fish by non-commercial shore-based fishing with line, spear, and net gears (left to right, respectively). Inset maps on each panel show examples of Marine Protected Areas (MPAs) with different gear restrictions. Only MPAs that completely prohibit use of the respective gears are shown on each panel. Upper inset = Lapakahi Marine Life Conservation District (MLCD): zone 1 is full no take, zone 2 allows line and net fishing but prohibits spearfishing. Lower inset = Waialeale Bay MLCD: line fishing is allowed but spear and net are prohibited.

<https://doi.org/10.1371/journal.pone.0189792.g004>



**Fig 5. Land-based pollution.** Maps of land-based pollution in central Maui Nui. From left to right: sedimentation (tons of sediment/yr/ha), nitrogen flux from onsite waste disposal systems (OSDS) (g/day/km<sup>2</sup>), and new development (scaled 0–1) which represents the impact of sediment runoff from recent construction sites on newly developed land between 2005–2011.

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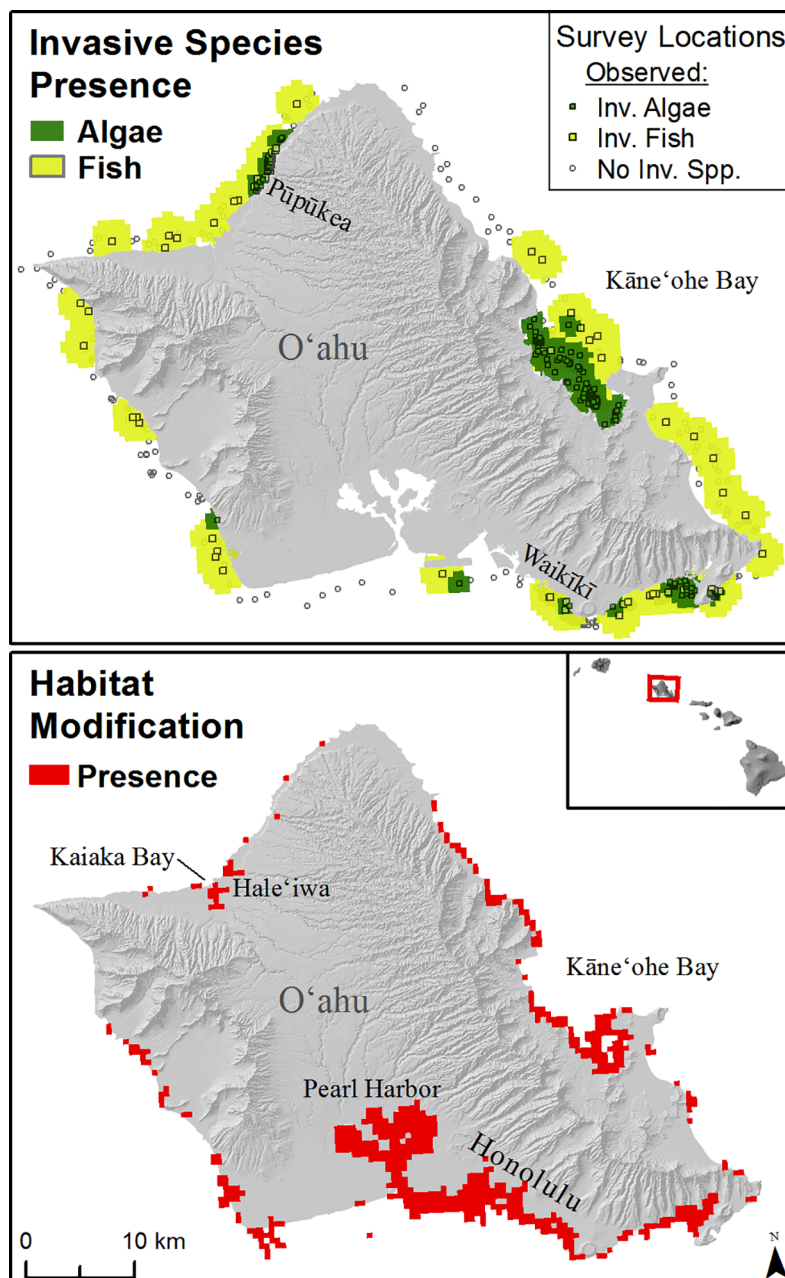
cause a blocking effect of ocean swells reaching islands located to the southeast, dramatically reducing the levels of wave energy hitting the coastlines of these islands. The blocking effect is readily seen in the long-term mean (Fig 7), climatological maximum and average annual maximum anomaly in wave forcing along the west coast of Lāna'i, Maui, and Hawai'i Island compared to that observed along the northwest coast of Ni'ihau, Kaua'i, and O'ahu.

**Sea surface temperature (SST).** SST exhibited a consistent spatial patterning across the MHI; windward facing coastlines of all islands had generally cooler ocean temperatures compared to leeward facing coastlines (Fig 7). The spatial pattern in SST was particularly amplified on Hawai'i Island, where the west side of the island was dominated by warmer ocean temperatures compared to the east side. The MHI are exposed to trade winds that blow from the northeast for a majority of the year. These winds drive vertical mixing of the upper water column, bringing cooler ocean temperatures to the near surface. As such, easterly facing coastlines exposed to trade winds predominantly have cooler SSTs compared to coastlines that are more sheltered.

**Irradiance.** Spatial distribution in irradiance showed no clear and consistent patterning across the MHI. Irradiance values were greatest along the southern coasts of O'ahu and Moloka'i, northeasterly coast of Lāna'i, and southwest coast of Maui (Fig 7). The southern half of the west coast of Hawai'i Island had the lowest long-term mean and climatological maximum irradiance values, but also had the greatest maximum anomaly values of any island.

**Chlorophyll-a.** Across the MHI, hotspots in chlorophyll-a were observed along the northwest shorelines of Kaua'i, O'ahu, and Maui and the south shore of Moloka'i (Fig 7). The greatest maximum anomalies were observed in the vicinity of Hilo on Hawai'i Island, near Haleiwa along the northwest shore of O'ahu, and much of the southwestern and northwestern shores





**Fig 6. Invasive species and habitat modification.** Top: Invasive species (presence only) on O'ahu, Hawai'i (green-invasive algae, yellow-invasive fish). Invasive algae layer is displayed on top of invasive fish. Bottom: Habitat modification (red) present on O'ahu, Hawai'i including manmade and artificial shorelines, maintained channels and dredged areas, and offshore aquaculture.

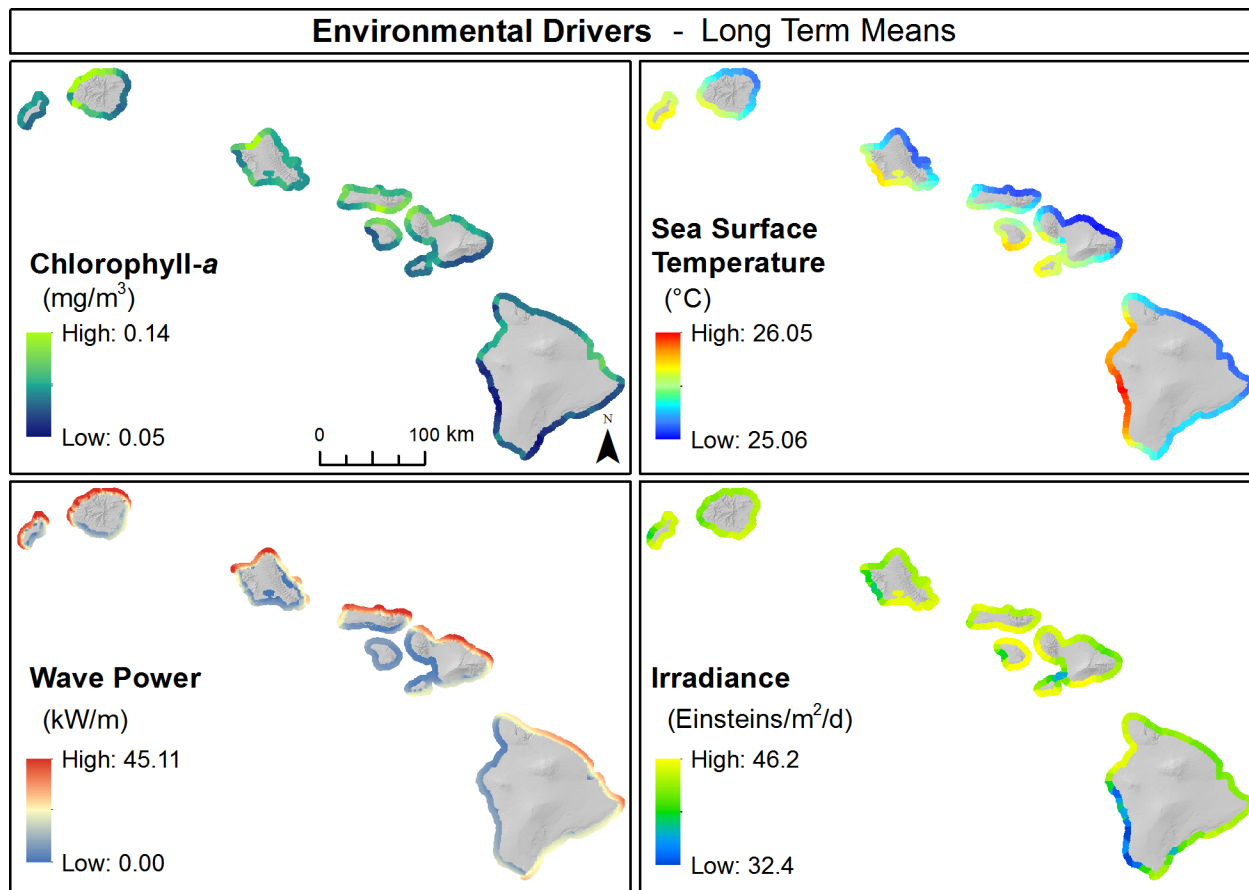
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of Kaua'i. The lowest chlorophyll-*a* was observed along south Maui, west Lāna'i, and the southeast and southwest coasts of Hawai'i Island.

### Driver correlations across islands

Anthropogenic drivers were variable across islands, and were generally greatest around O'ahu, the most densely populated island (Fig 8). Habitat modification on O'ahu was correlated with



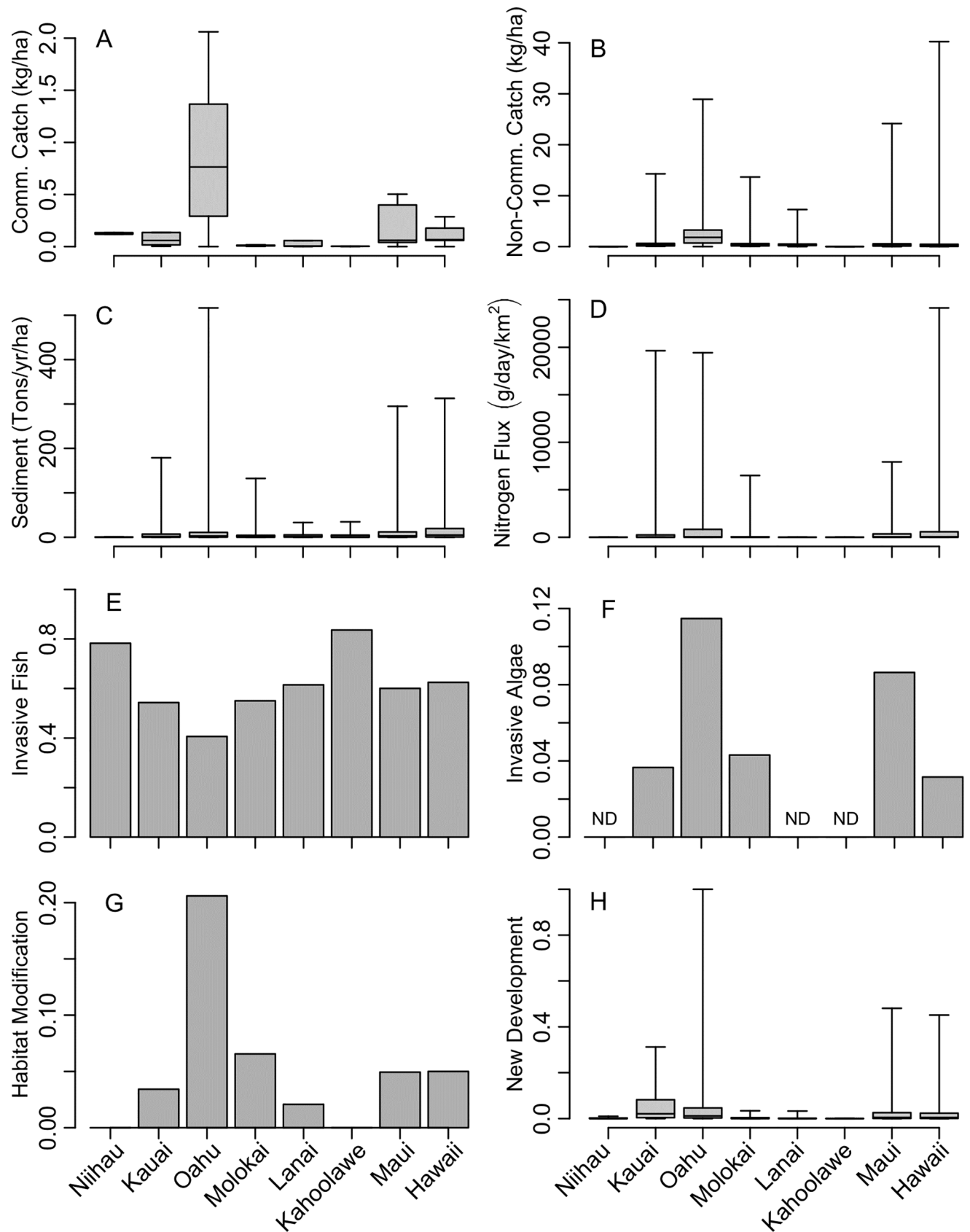


**Fig 7. Environmental drivers.** Spatial distributions in key environmental drivers that influence coral reef ecosystems, including chlorophyll-*a* ( $\text{mg m}^{-3}$ ), sea surface temperature ( $^{\circ}\text{C}$ ), wave power ( $\text{kW m}^{-1}$ ), and irradiance ( $\text{Einstein m}^{-2} \text{d}^{-1}$ ) across the eight main Hawaiian Islands.

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the introduction of invasive algae and pressure from fishing. In addition, commercial fish catch was greatest and most variable around O'ahu, and low around Kaho'olawe, where catch for nearshore fish is highly restricted (Fig 8A). Across islands, non-commercial fish catch was more variable than commercial catch (Fig 8B), and overall ranges were as much as 20 times larger than commercial catch [50]. Sedimentation and nitrogen flux were also variable and had skewed distributions with extremely high values on O'ahu, Maui, and Hawai'i (Fig 8C and 8D). Invasive fish presence was frequent across all islands, and invasive algae were greatest on O'ahu, followed by Maui (Fig 8E and 8F). Habitat modification was greatest on O'ahu and was 5 times greater than any other island (Fig 8G). New development was also greatest on O'ahu, however Kaua'i had more widespread higher levels of development (median and 75<sup>th</sup> quartile) compared to other islands (Fig 8H).

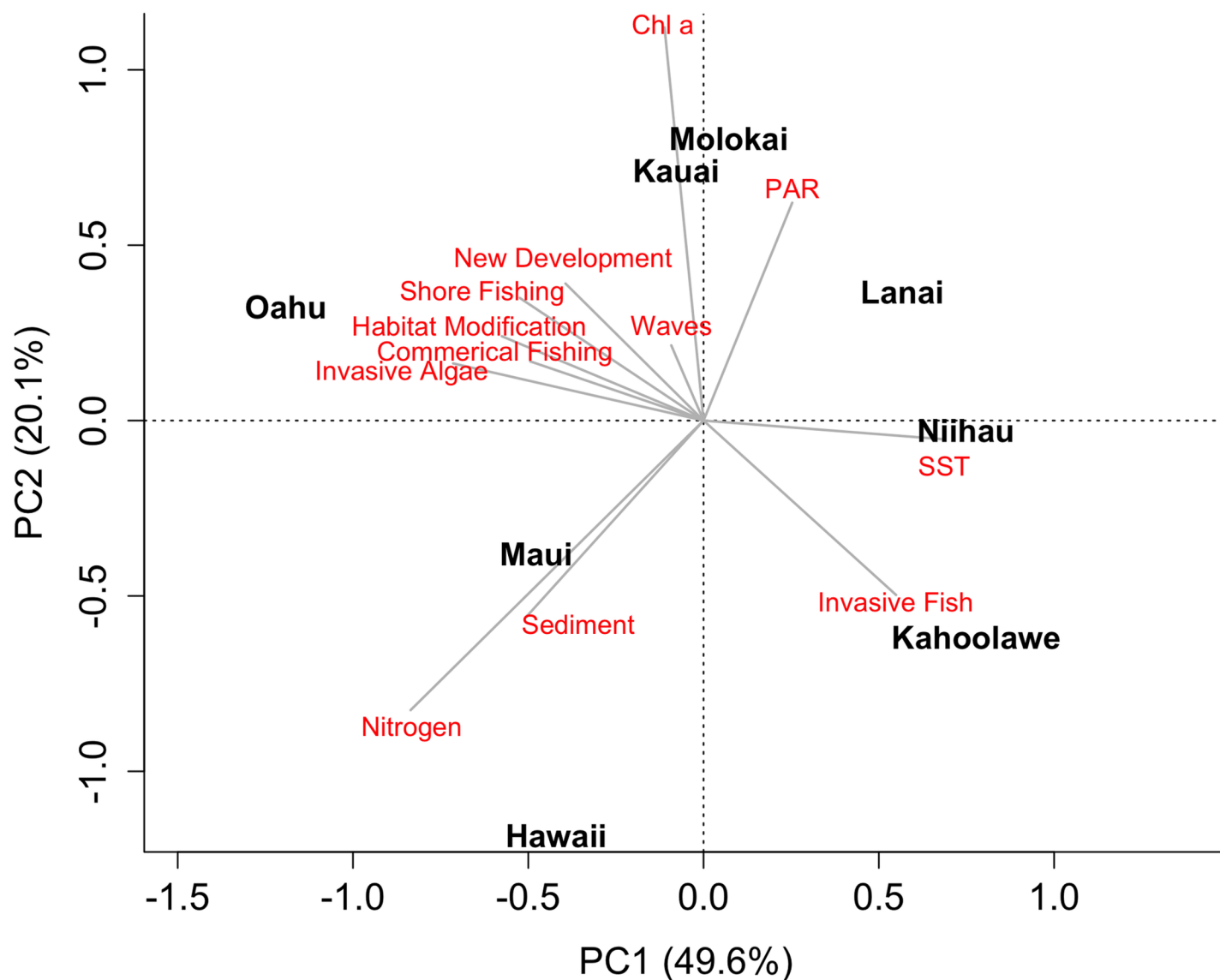
When both anthropogenic and environmental drivers were considered together in multidimensional space, islands clustered differently according to their correlation with particular variables (Fig 9). The first two axes of the PCA explained 69.7% of the variability contained in the 12 predictor variables used. The first axis (PC1), which was responsible for the majority of the variance explained (49.6%), clearly separated O'ahu from all other islands, and was strongly correlated with fishing, habitat modification, new development, and invasive algae. Maui and Hawai'i were also correlated with the same variables, but sediment and nutrients were also high and separated these two islands from the others. Notably, none of the environmental drivers



**Fig 8. Primary anthropogenic drivers.** Distributions of primary proximate anthropogenic drivers by island for the main Hawaiian Islands ordered from north to south. Box plots represent minimum, 1<sup>st</sup> quartile, mean, 3<sup>rd</sup> quartile, and maximum for each continuous driver, and categorical drivers (i.e. presence) are histograms of frequency of occurrence. Drivers include (A) total commercial catch for all gears combined (kg/ha), (B) total non-commercial catch for all gears combined (kg/ha), (C) sediment (Tons/yr/ha), (D) nitrogen flux from OSDS (g/day/km<sup>2</sup>), (E) invasive fish, (F) invasive algae, (G) habitat modification (proportion of reef area with presence), (H) new development (unitless).

<https://doi.org/10.1371/journal.pone.0189792.g008>

were strongly associated with O'ahu, whereas Kaua'i, Moloka'i, and Lāna'i were all correlated with environmental drivers with higher values of chlorophyll-*a*, irradiance, and waves. Lāna'i and Ni'ihau were most correlated with SST. Kaho'olawe was oriented opposite to O'ahu, reflecting low values of all anthropogenic drivers except for high numbers of invasive fishes.



**Fig 9. Principle component analysis of anthropogenic and environmental drivers.** Principle component analysis (PCA) of the anthropogenic and environmental drivers based on median values by island. Loadings for each principle component drawn as grey lines in the direction of increasing values. PAR = Photosynthetically Active Radiation (irradiance); Chl a = Chlorophyll-*a*.

<https://doi.org/10.1371/journal.pone.0189792.g009>

## Discussion

### Advancing spatial data integration

Integrating large and disparate data types presents new challenges in how we analyze, synthesize, and visualize information. However, the amount of data now available offers an unprecedented opportunity for understanding coral reefs and informing management decisions at multiple scales [82]. Our approach acknowledges that coral reef ecosystem dynamics are social-ecological, and driven by a combination of biotic processes, abiotic conditions and human drivers, and provides a novel integration of environmental and anthropogenic driver data across a regional coral reef system. This case study allowed us to establish and operationalize a methodological approach to spatially integrate data sets on coral reefs. The stepwise methodological approach we developed and conducted can be applied to future studies in order to leverage the power of extensive spatio-temporal data, inform pressing problems facing coral reefs, and better manage for ecosystem resilience to avoid coral reef tipping points.

The spatially explicit datasets on anthropogenic impacts in this study have advanced well beyond using just human population density and revealed a more explicit understanding of the spatial heterogeneity of human and natural drivers across a coral reef seascape. In addition, this work builds on recent coral reef anthropogenic driver advances by Cinner et al. [83] that incorporated distance to market and other social metrics, and provides a methodological approach to integrate environmental drivers. At a regional-scale, it is possible to assess proximate drivers with much greater accuracy, which is precluded in global analyses that often rely on proxy data. The regional-scale approach supports the understanding of complex dynamics governing ecosystem state, and therefore the policy interventions most likely to be successful using a place-based approach. With significant climatological changes predicted to occur in the coming decades, it is increasingly important to understand the major environmental and physical forces impacting coral reefs and the effects these environmental forces may have on the biology and management of the ecosystem. As a result, key natural environmental drivers, such as wave forcing, must be incorporated to more fully and accurately assess how these drivers relate to different reef states. Our synthesis and mapping of these comprehensive high-resolution spatial datasets of known key drivers of coral reef ecosystem state provides a pathway in understanding integrated social-ecological disturbance regimes.

### Anthropogenic drivers

**Fisheries catch.** The development of the fisheries catch layers provides an in-depth illustration of the design phase process of the methodological approach. The iterative engagement with experts and managers was a critical step to vet the fisheries catch spatial model and output. It is important to advance the mapping of fishing effort beyond simple proxies of human population density because severe declines in reef fish populations have long been documented for reefs both near and far from human population centers in Hawai'i [31,20]. For example, in a recent global analysis of how coral reef fish biomass relates to the density of local human populations, high variability in fisheries conditions at low human population densities resulted in relatively weak explanatory models [24]. Our analytical approach in this study has progressed beyond a single proxy; by taking shoreline accessibility and boat access into account, we provide further levels of detail to visualize and map fishing effort by gear type across the State. Though human population was not used, island-scale demographics still play a role in the fisheries catch layers as O'ahu has the highest boat ownership and the greatest number of launch ramps; thus, at the island scale, human population density does appear to be driving boat-based fisheries catch levels.

The nearshore fisheries catch driver datasets provided an interesting spatial characterization of fishing across the MHI that highlighted unique contrasts in shore-based catch per unit area by distinct gear types. Accessibility is an especially important component when considering shoreline fishing in Hawai'i, as limited availability of roads and steep cliffs drastically constrain fishing effort from shore in many areas across the state [20]. This is typically the case on Hawai'i Island, and partly what drives the shore-based line and spear catch per unit area values higher than any other island across the state. Stamoulis et al. [84] showed the distribution of targeted reef fish biomass to be focused in remote and inaccessible areas across the Main Hawaiian Islands. Wave exposure on many NW facing shores can also have a significant effect on fishing accessibility, in particular large winter swells make north exposed shores inaccessible to fishing and make many of these areas de facto reserves for part of the year during high wave seasons [66,85–86].

These nearshore fisheries catch datasets reveal that very few locations in the Main Hawaiian Islands are exempt from fishing. No-take marine managed areas only account for 0.4% of nearshore (0–18m) waters in the state [87]. Large areas with little to no fishing pressure are those with restricted access such as the islands of Ni'ihau and Kaho'olawe, followed by inaccessible areas such as the North shore of Moloka'i and portions of the NE (Hamakua) and SE coasts of Hawai'i island. Not surprisingly, these same locations have been shown to harbor high biomass of targeted reef fishes [84].

The spatial patterns of shore-based fishing by gear type also highlight unique place-based preferences depending on target species and the dominant coastal habitats present that influence gear selection. Understanding and mapping the main gear types driving fish catch per unit area can support spatial management of fisheries across the islands by highlighting potential hotspots for management by gear type, bag or slot limits. McCoy [50] demonstrated that each fishing gear type in Hawai'i targets distinct sets of species. The next steps for marine spatial planning applications could include a combination of this species-level knowledge, together with stakeholder input and the map outputs from this study in order to inform the designation of marine managed areas and implementation of harvest control rules for the conservation of key resource species (e.g., as proposed by Rassweiler et al. [88]).

**Land-based stressors.** Sediment is associated with nutrients and other forms of contaminants that are bound by organic matter and the iron-aluminum oxides that are typical of many of the highly weathered soils of the MHI. For instance, Wiegner et al. [89] found that 73% of the total phosphorus load and 43% of the total nitrogen load along windward Hawai'i Island streams were bound to sediments. The coastal patterns of land-based pollution offer insight into where integrated land-sea management might be critical to achieving nearshore ecological goals (e.g., as evaluated in Maui by Oleson et al. [90]). In areas with acute land-based stressors, or in areas where land-based pollution might have direct, high economic costs (e.g., tourism areas), it may be necessary to mitigate the land-based stressors.

Generally, the windward (east-facing) streams with high sediment discharge on open coastlines have lower sediment residence times due to environmental conditions (e.g., wave energy, currents, bathymetry) compared to enclosed embayments. Residence time is important in the impact of sediment on reef quality in Hawai'i [91]. For instance, we found Pelekane Bay on the western coast of Hawai'i Island to have a high sediment load, which was derived from the adjacent watershed that discharges into a small, shallow harbor. This finding is supported by other recent field-based work in this area [92]. Research from elsewhere in Hawai'i indicates that localized sediment plumes are common even during small storm events [93].

**Environmental drivers.** The Hawaiian Islands are exposed to large fluctuations in environmental forcings compared to other coral reef ecosystems across the Pacific Ocean [45]. Analysis of key environmental drivers presented herein indicates that even within the eight

MHI, substantial gradients in drivers exist both among and within islands (Fig 7). For example, Hawai'i receives wintertime ocean swells generated in the North Pacific that produce extremely large wave events (wave heights in excess of 7 m) several times in an average year [94]. Because these events are generated in the northwest, the northwesterly exposed coastlines receive the highest levels of wave forcing with many of the more sheltered coastal regions receiving much lower levels (an order of magnitude or more) of wave forcing. Variations in wave forcing influences important ecological processes such as coral reef development [95], and spatiotemporal patterning in benthic and reef fish communities [96]. Waves can also drive strong currents and nearshore mixing, which can influence sediment transport and resuspension [97], and reduce ocean temperatures during warming events [98].

Chlorophyll-*a*, a proxy for phytoplankton biomass and an indicator of phytoplankton production, exhibited large spatial variability across the MHI. Kaua'i, O'ahu and the region between Maui, Moloka'i, and Lāna'i showed long-term enhancements in chlorophyll-*a*, while a high frequency of anomalies were observed along south Moloka'i, south Maui, and the northwest coast of Hawai'i Island. These observed differences in chlorophyll-*a* were presumably indicative of changes in local nutrient concentrations, which can increase through a variety of natural process such as upwelling and mixing, and through human-related process such as agricultural run-off and poor waste-water management. Increases in phytoplankton biomass can impact multiple trophic groups within coral reef food-webs, promoting the development of calcium carbonate forming benthic organisms, namely scleractinian (hard) corals and crustose coralline algae [4], as well as the biomass of planktivorous and piscivorous fishes [4]. However, human-induced changes in phytoplankton biomass may result in negative ecological consequences, such as toxic algal blooms and coastal eutrophication [99].

### Linking science to policy and management through effective communication

These datasets will allow improved understanding of what drives variation in Hawaiian reefs and support management designed to promote reef resilience and protect reef ecosystem services. The spatial data synthesis from this project has been made publicly available to allow managers, researchers and members of the public to explore the data. In addition, this approach also serves to connect expert spatial analysts with new datasets, which will allow for future analysis and understanding of what drives variation on coral reefs. The goals of serving these data widely, and at no end-user cost, is to facilitate use of the data synthesis framework in further research and provide a scientific basis for improved policy and management actions at the state level through engagement with Hawai'i Division of Aquatic Resources (DAR) and other management agencies. Our project is sharing information and building connections in Hawai'i through a variety of flexible formats, including story mapping and data visualizations. The science communication approach was implemented in order to bridge the technology barrier by allowing users to easily explore mapped data without previous mapping technology experience.

We have also distilled our scientific outputs and served this information across several platforms that allow for visualization of mapped reef drivers in an interactive, user-friendly online mapping interface as well as static map products ([www.pacioos.hawaii.edu/projects/oceantip-pingpoints](http://www.pacioos.hawaii.edu/projects/oceantip-pingpoints)). Our approach will allow scientists, policy-makers, and community members to access information in the format that meets their analytical or information needs. For example, the NOAA Integrated Ecosystem Assessment program is currently leveraging these datasets to investigate temporal trends in coral reef monitoring data and guide research in identifying local drivers that undermine or promote coral reef health and resilience on the west coast of Hawai'i Island, which in-turn supports current management decision efforts by local State agencies.



Specifically, NOAA is investigating what drivers best explain temporal trends in monitoring data, as well as patterns of bleaching and recovery from the 2014/2015 mass bleaching events.

## Applications to support spatial management and policy

Currently, less than 0.4% of coral reef ecosystems in the main Hawaiian Islands are protected through no-take marine protected areas (MPAs) [100, 87]. Advancing coastal management in Hawai'i will involve developing tailored management strategies to control key stressors such that nearshore ecosystems and the ecosystem goods and services they supply are sustained. To move toward more effective marine resource management, there is a need to integrate 'place-based' management approaches together with holistic marine spatial planning that ensures patterns of connectivity and disturbance are managed across the seascapes [101–103]. One of the first steps in such marine spatial planning efforts involves mapping and integrating biophysical and human dimensions, including drivers and human uses, across the entire ecosystem [104–107]. However, the lack of comprehensive, spatially explicit data and spatial data integration methods can impede holistic, ecosystem-scale ocean planning and area-based management [82]. Our research reveals a pragmatic approach to assess these complex drivers and their spatial distribution and intensity across a regional seascape. While our focus has been on the nearshore reef environment, additional anthropogenic stressors, like pelagic fisheries, commercial shipping, recreational activity, marine debris, and military activity also need to be mapped to support marine spatial planning in intertidal and deeper habitats. Further, analysis could also examine how these anthropogenic and environmental drivers interact, as well as integrating anthropogenic impact drivers together with information on social benefits from seascapes (ecosystem services) [108, 104].

While strength of this methodological approach will vary based on the available data sets, equally critical is the success of stakeholder engagement and the distillation and synthesis involved in science communication and outreach efforts. Data collected for research purposes often fails to meet decision-maker needs, e.g., by ignoring management constraints or stakeholder objectives, and thus is rarely used to affect decisions [109]. The true utility of harnessing the power of large data sets lies in the distillation of these data into knowledge in a way that can effectively provide the best available science to inform management and policy. Ideally, each step in the methodological process will involve iterative discussion and engagement with stakeholders and end users (e.g., managers, policy-makers) to address their individual goals and needs, enabling development of a final product that is ready for implementation by management and uptake by the stakeholder community [88]. Co-creation of knowledge by researchers, data users and stakeholders is fundamental to ensuring that knowledge is provided in metrics that resonate with stakeholder objectives, is in a format that can be analyzed by end users for guiding decisions (e.g., via tradeoff analysis; [110–111]), and will remain relevant for adaptive governance [109, 112–113]. Managers and decision-makers in Hawai'i recognize the need for data generally and ecosystem services knowledge specifically [114–115], and have been intimately involved in every step. Iterative engagement with the end users and stakeholders is built into the methods outlined here, allowing their needs and objectives to be identified, reviewed, and ultimately addressed. Accurate, publicly available data provide transparency and support effective, timely, science-based decision-making, which should lead to more effective management of these valuable resources that mean so much to so many.

## Supporting information

**S1 Supplement. Driver data analysis, assumptions, and limitations.**  
(DOCX)

**S2 Supplement. Detailed GIS methods used to create fisheries catch maps.**  
(DOCX)

**S3 Supplement. Correlation matrix for driver layers used in PCA.**  
(XLSX)

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## Author Contributions

**Conceptualization:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Mary K. Donovan, Gareth J. Williams, Jean-Baptiste Jouffray, Larry B. Crowder, Ashley Erickson, Alan M. Friedlander, Carrie V. Kappel, John N. Kittinger, Albert Norström, Magnus Nyström, Kirsten L. L. Oleson, Crow White, Kimberly A. Selkoe.

**Data curation:** Lisa M. Wedding.

**Formal analysis:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Hilary R. Walecka, Mary K. Donovan, Gareth J. Williams, Jean-Baptiste Jouffray, Kim Falinski, Kaylyn McCoy.

**Funding acquisition:** Larry B. Crowder, Ashley Erickson, Alan M. Friedlander, John N. Kittinger, Kirsten L. L. Oleson, Kimberly A. Selkoe.

**Investigation:** Lisa M. Wedding.

**Methodology:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Hilary R. Walecka, Mary K. Donovan, Gareth J. Williams, Jean-Baptiste Jouffray, Kim Falinski, Alan M. Friedlander, Carrie V. Kappel, Kaylyn McCoy, Kostantinos A. Stamoulis, Crow White, Kimberly A. Selkoe.

**Project administration:** Larry B. Crowder, Ashley Erickson, Alan M. Friedlander, Carrie V. Kappel, John N. Kittinger, Albert Norström, Magnus Nyström, Kirsten L. L. Oleson, Kimberly A. Selkoe.

**Supervision:** Larry B. Crowder, Ashley Erickson, Alan M. Friedlander, Carrie V. Kappel, John N. Kittinger, Albert Norström, Magnus Nyström, Kirsten L. L. Oleson, Kimberly A. Selkoe.

**Validation:** Lisa M. Wedding, Joey Lecky, Kim Falinski.

**Visualization:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Hilary R. Walecka, Mary K. Donovan.

**Writing – original draft:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Hilary R. Walecka, Mary K. Donovan, Gareth J. Williams, Jean-Baptiste Jouffray, Larry B. Crowder, Ashley

Erickson, Kim Falinski, Alan M. Friedlander, Carrie V. Kappel, John N. Kittinger, Albert Norström, Magnus Nyström, Kirsten L. L. Oleson, Kostantinos A. Stamoulis, Crow White, Kimberly A. Selkoe.

**Writing – review & editing:** Lisa M. Wedding, Joey Lecky, Jamison M. Gove, Hilary R. Walecka, Mary K. Donovan, Gareth J. Williams, Jean-Baptiste Jouffray, Larry B. Crowder, Kim Falinski, Alan M. Friedlander, Carrie V. Kappel, John N. Kittinger, Albert Norström, Magnus Nyström, Kirsten L. L. Oleson, Kostantinos A. Stamoulis, Crow White, Kimberly A. Selkoe.

## References

- Gove JM, Williams GJ, McManus MA, Clark SJ, Ehse JS, Wedding LM. Coral reef benthic regimes exhibit non-linear threshold responses to natural physical drivers. *Marine Ecology Progress Series*. 2015 Mar 2; 522:33–48.
- Williams GJ, Smith JE, Conklin EJ, Gove JM, Sala E, Sandin SA. Benthic communities at two remote Pacific coral reefs: effects of reef habitat, depth, and wave energy gradients on spatial patterns. *PeerJ*. 2013 May 28; 1:e81. <https://doi.org/10.7717/peerj.81> PMID: 23734341
- Norström AV, Nyström M, Jouffray JB, Folke C, Graham NA, Moberg F, et al. Guiding coral reef futures in the Anthropocene. *Frontiers in Ecology and the Environment*. 2016 Nov 1; 14(9):490–8.
- Williams ID, Baum JK, Heenan A, Hanson KM, Nadon MO, Brainard RE. Human, oceanographic and habitat drivers of central and western Pacific coral reef fish assemblages. *PLoS One*. 2015 Apr 1; 10(4):e0120516. <https://doi.org/10.1371/journal.pone.0120516> PMID: 25831196
- Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'agrosa C, et al. A global map of human impact on marine ecosystems. *Science*. 2008 Feb 15; 319(5865):948–52. <https://doi.org/10.1126/science.1149345> PMID: 18276889
- Bellwood DR, Hughes TP, Folke C, Nyström M. Confronting the coral reef crisis. *Nature*. 2004 Jun 24; 429(6994):827. <https://doi.org/10.1038/nature02691> PMID: 15215854
- Nyström M, Folke C, Moberg F. Coral reef disturbance and resilience in a human-dominated environment. *Trends in Ecology & Evolution*. 2000 Oct 1; 15(10):413–7.
- Nyström M, Folke C. Spatial resilience of coral reefs. *Ecosystems*. 2001 Aug 1; 4(5):406–17.
- Mumby PJ, Hastings A, Edwards HJ. Thresholds and the resilience of Caribbean coral reefs. *Nature*. 2007 Nov 1; 450(7166):98. <https://doi.org/10.1038/nature06252> PMID: 17972885
- Nyström M, Graham NA, Lokrantz J, Norström AV. Capturing the cornerstones of coral reef resilience: linking theory to practice. *Coral Reefs*. 2008 Dec 1; 27(4):795–809.
- Hughes TP, Graham NA, Jackson JB, Mumby PJ, Steneck RS. Rising to the challenge of sustaining coral reef resilience. *Trends in ecology & evolution*. 2010 Nov 30; 25(11):633–42.
- Graham NA, Cinner JE, Norström AV, Nyström M. Coral reefs as novel ecosystems: embracing new futures. *Current Opinion in Environmental Sustainability*. 2014 Apr 30; 7:9–14.
- Roff G, Mumby PJ. Global disparity in the resilience of coral reefs. *Trends in Ecology & Evolution*. 2012 Jul 31; 27(7):404–13.
- Norström AV, Nyström M, Lokrantz J, Folke C. Alternative states on coral reefs: beyond coral–macroalgal phase shifts. *Marine ecology progress series*. 2009 Feb 11; 376:295–306.
- Jouffray JB, Nyström M, Norström AV, Williams ID, Wedding LM, Kittinger JN, et al. Identifying multiple coral reef regimes and their drivers across the Hawaiian archipelago. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*. 2015 Jan 5; 370(1659):20130268.
- Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. Catastrophic shifts in ecosystems. *Nature*. 2001 Oct 11; 413(6856):591. <https://doi.org/10.1038/35098000> PMID: 11595939
- Daskalov GM, Grishin AN, Rodionov S, Mihneva V. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. *Proceedings of the National Academy of Sciences*. 2007 Jun 19; 104(25):10518–23.
- Nyström M, Norström AV, Blenckner T, de la Torre-Castro M, Eklöf JS, Folke C, et al. Confronting feedbacks of degraded marine ecosystems. *Ecosystems*. 2012 Aug 1; 15(5):695–710.
- Rocha J, Yletyinen J, Biggs R, Blenckner T, Peterson G. Marine regime shifts: drivers and impacts on ecosystems services. *Phil. Trans. R. Soc. B*. 2015 Jan 5; 370(1659):20130273.

20. Williams ID, Walsh WJ, Schroeder RE, Friedlander AM, Richards BL, Stamoulis KA. Assessing the importance of fishing impacts on Hawaiian coral reef fish assemblages along regional-scale human population gradients. *Environmental Conservation*. 2008 Sep; 35(3):261–72.
21. Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, et al. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science*. 2008 Jul 25; 321(5888):560–3. <https://doi.org/10.1126/science.1159196> PMID: 18653892
22. Mora C. A clear human footprint in the coral reefs of the Caribbean. *Proceedings of the Royal Society of London B: Biological Sciences*. 2008 Apr 7; 275(1636):767–73.
23. Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, et al. Coral reefs under rapid climate change and ocean acidification. *science*. 2007 Dec 14; 318(5857):1737–42. <https://doi.org/10.1126/science.1152509> PMID: 18079392
24. Cinner JE, Graham NA, Huchery C, MacNeil MA. Global effects of local human population density and distance to markets on the condition of coral reef fisheries. *Conservation Biology*. 2013 Jun 1; 27(3):453–8. <https://doi.org/10.1111/j.1523-1739.2012.01933.x> PMID: 23025334
25. Mayer-Schönberger V. and Cukier K., 2013. Big data: A revolution that will transform how we live, work, and think. Houghton Mifflin Harcourt.
26. Hampton SE, Strasser CA, Tewksbury JJ, Gram WK, Budden AE, Batcheller AL, et al. Big data and the future of ecology. *Frontiers in Ecology and the Environment*. 2013 Apr 1; 11(3):156–62.
27. Halpern BS, Frazier M, Potapenko J, Casey KS, Koenig K, Longo C, et al. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature communications*. 2015 Jul 14; 6.
28. MacNeil MA, Graham NA, Cinner JE, Wilson SK, Williams ID, Maina J, et al. Recovery potential of the world's coral reef fishes. *Nature*. 2015 Apr 16; 520(7547):341–4. <https://doi.org/10.1038/nature14358> PMID: 25855298
29. Cinner JE, Pratchett MS, Graham NA, Messmer V, Fuentes MM, Ainsworth T, et al. A framework for understanding climate change impacts on coral reef social–ecological systems. *Regional environmental change*. 2016 Apr 1; 16(4):1133–46.
30. Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, et al. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability science*. 2012 Feb 1; 7(1):25–43.
31. Friedlander A, Aeby G, Balwani S, Bowen B, Brainard R, et al. 2008. The state of coral reef ecosystems of the Northwestern Hawaiian Islands. In: Waddell J, Clarke A The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. Silver Spring, MD: NOAA Technical Memorandum NOS NCCOS 73.
32. Hunter CL, Evans CW. Coral reefs in Kaneohe Bay, Hawaii: two centuries of western influence and two decades of data. *Bulletin of Marine Science*. 1995 Sep 1; 57(2):501–15.
33. Stimson J, Larned S, Conklin E. Effects of herbivory, nutrient levels, and introduced algae on the distribution and abundance of the invasive macroalga *Dictyosphaeria cavernosa* in Kaneohe Bay, Hawaii. *Coral Reefs*. 2001 May 1; 19(4):343–57.
34. Bahr KD, Jokiel PL, Toonen RJ. The unnatural history of Kāne 'ohe Bay: coral reef resilience in the face of centuries of anthropogenic impacts. *PeerJ*. 2015 May 12; 3:e950. <https://doi.org/10.7717/peerj.950> PMID: 26020007
35. Abbott IA. Marine red algae of the Hawaiian Islands. Bishop Museum Pr; 1999.
36. Randall JE. Reef and shore fishes of the Hawaiian Islands. Sea Grant College Program, University of Hawai'i; 2007.
37. Briggs JC, Bowen BW. A realignment of marine biogeographic provinces with particular reference to fish distributions. *Journal of Biogeography*. 2012 Jan 1; 39(1):12–30.
38. Kay EA, Palumbi SR. Endemism and evolution in Hawaiian marine invertebrates. *Trends in Ecology & Evolution*. 1987 Jul 1; 2(7):183–6.
39. DeMartini EE, Friedlander AM. Spatial patterns of endemism in shallow-water reef fish populations of the Northwestern Hawaiian Islands. *Marine Ecology Progress Series*. 2004 Apr 28; 271:281–96.
40. Maragos JE, Potts DC, Aeby GS, Gulko D, Kenyon J, Siciliano D, et al. 2000–2002 Rapid Ecological Assessment of corals (Anthozoa) on shallow reefs of the Northwestern Hawaiian Islands. Part 1: Species and distribution. *Pacific Science*. 2004; 58(2):211–30.
41. Cesar HS, Van Beukering P. Economic valuation of the coral reefs of Hawai'i. *Pacific Science*. 2004; 58(2):231–42.
42. Friedlander AM, Nowlis J, Koike H. Improving Fisheries Assessments Using Historical Data. *Marine Historical Ecology in Conservation: Applying the Past to Manage for the Future*. 2014 Dec 24:91.

43. Friedlander AM, DeMartini EE. Contrasts in density, size, and biomass of reef fishes between the northwestern and the main Hawaiian islands: the effects of fishing down apex predators. *Marine Ecology Progress Series*. 2002 Apr 5; 230:253–64.
44. Kittinger J, Finkbeiner E, Glazier E, Crowder L. Human dimensions of coral reef social-ecological systems. *Ecology and Society*. 2012 Nov 16; 17(4).
45. Gove JM, Williams GJ, McManus MA, Heron SF, Sandin SA, Vetter OJ, et al. Quantifying climatological ranges and anomalies for Pacific coral reef ecosystems. *PloS one*. 2013 Apr 18; 8(4):e61974. <https://doi.org/10.1371/journal.pone.0061974> PMID: 23637939
46. Smith MK. An ecological perspective on inshore fisheries in the main Hawaiian Islands. *Marine Fisheries Review*. 1993; 55(2):34–49.
47. Friedlander AM, Parrish JD. Fisheries harvest and standing stock in a Hawaiian Bay. *Fisheries Research*. 1997 Oct 31; 32(1):33–50.
48. Tissot BN, Walsh WJ, Hixon MA. Hawaiian Islands marine ecosystem case study: ecosystem-and community-based management in Hawaii. *Coastal Management*. 2009 May 5; 37(3–4):255–73.
49. Kittinger JN, Teneva LT, Koike H, Stamoulis KA, Kittinger DS, Oleson KL, et al. From reef to table: social and ecological factors affecting coral reef fisheries, artisanal seafood supply chains, and seafood security. *PloS one*. 2015 Aug 5; 10(8):e0123856. <https://doi.org/10.1371/journal.pone.0123856> PMID: 26244910
50. McCoy K. Estimating nearshore fisheries catch for the main Hawaiian Islands. Unpublished master's thesis, The University of Hawaii at Manoa, Honolulu, Hawaii. 2015.
51. Fabricius KE. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine pollution bulletin*. 2005 Feb 28; 50(2):125–46. <https://doi.org/10.1016/j.marpolbul.2004.11.028> PMID: 15737355
52. Kuntz NM, Kline DI, Sandin SA, Rohwer F. Pathologies and mortality rates caused by organic carbon and nutrient stressors in three Caribbean coral species. *Marine Ecology Progress Series*. 2005 Jun 9; 294:173–80.
53. Vermeij MJ, Van Moorselaar I, Engelhard S, Hörnlein C, Vonk SM, Visser PM. The effects of nutrient enrichment and herbivore abundance on the ability of turf algae to overgrow coral in the Caribbean. *PloS one*. 2010 Dec 13; 5(12):e14312. <https://doi.org/10.1371/journal.pone.0014312> PMID: 21179215
54. Sharp R, Tallis HT, Ricketts T, Guerry AD, Wood SA, Chaplin-Kramer R et al. InVEST 3.2 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. 2015.
55. Hamel P, Chaplin-Kramer R, Sim S, Mueller C. A new approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA. *Science of the Total Environment*. 2015 Aug 15; 524:166–77. <https://doi.org/10.1016/j.scitotenv.2015.04.027> PMID: 25897725
56. Falinski KA. Predicting sediment export into tropical coastal ecosystems to support ridge to reef management (Doctoral dissertation, University of Hawai'i at Manoa).
57. Falinski KA, Oleson K, Htun H, Kappel C, Lecky J, Rowe C, et al. Using an ecosystem service decision support tool to support ridge to reef management: An example of sediment reduction in west Maui, Hawaii. In American Geophysical Union, Ocean Sciences Meeting 2016, abstract# P52A-08 2016 Feb.
58. Dailer ML, Knox RS, Smith JE, Napier M, Smith CM. Using  $\delta^{15}\text{N}$  values in algal tissue to map locations and potential sources of anthropogenic nutrient inputs on the island of Maui, Hawai'i, USA. *Marine Pollution Bulletin*. 2010 May 31; 60(5):655–71. <https://doi.org/10.1016/j.marpolbul.2009.12.021> PMID: 20070989
59. McClanahan TR, Carreiro-Silva M, DiLorenzo M. Effect of nitrogen, phosphorous, and their interaction on coral reef algal succession in Glover's Reef, Belize. *Marine Pollution Bulletin*. 2007 Dec 31; 54(12):1947–57. <https://doi.org/10.1016/j.marpolbul.2007.09.023> PMID: 17963793
60. Smith JE, Runcie JW, Smith CM. Characterization of a large-scale ephemeral bloom of the green alga *Cladophora sericea* on the coral reefs of West Maui, Hawai'i. *Marine Ecology Progress Series*. 2005 Nov 4; 302:77–91.
61. Whittier RB, El-Kadi AI. Human and Environmental Risk Ranking of Onsite Sewage Disposal Systems, Final. Department of Geology & Geophysics, University of Hawaii at Manoa. 2009 Dec.
62. Whittier RB, El-Kadi A. Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian Islands of Kauai, Molokai, Maui, and Hawaii. Final report prepared for State of Hawai'i Department of Health. Safe Drinking Water Branch. 2014 Sep.



63. Ostrander CE, McManus MA, DeCarlo EH, Mackenzie FT. Temporal and spatial variability of freshwater plumes in a semienclosed estuarine–bay system. *Estuaries and Coasts*. 2008 Feb 1; 31(1):192.
64. Smith JE, Hunter CL, Smith CM. Distribution and reproductive characteristics of nonindigenous and invasive marine algae in the Hawaiian Islands. *Pacific Science*. 2002; 56(3):299–315.
65. Randall JE. Introductions of marine fishes to the Hawaiian Islands. *Bulletin of Marine Science*. 1987 Sep 1; 41(2):490–502.
66. Friedlander AM, Donovan MK, Stamoulis KA, Williams ID, Brown EK, Conklin EJ, et al. 2017 Human-induced gradients of reef fish declines in the Hawaiian Archipelago viewed through the lens of traditional management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 1–12.
67. Costa, B.M. and M.S. Kendall (eds.). 2016. Marine Biogeographic Assessment of the Main Hawaiian Islands. Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration. OCS Study BOEM 2016–035 and NOAA Technical Memorandum NOS NCCOS 214. 359 pp.
68. Meyer AL. An ecological comparison of *Cephalopholis argus* between native and introduced populations. 2008.
69. Friedlander M, Parrish JD, DeFelice RC. Ecology of the introduced snapper *Lutjanus kasmira* (Forsskal) in the reef fish assemblage of a Hawaiian bay. *Journal of Fish Biology*. 2002 Jan 1; 60(1):28–48.
70. Smith JE, Hunter CL, Conklin EJ, Most R, Sauvage T, Squair C, et al. Ecology of the invasive red alga *Gracilaria salicornia* (Rhodophyta) on O‘ahu, Hawai‘i. *Pacific science*. 2004; 58(2):325–43.
71. Kilpatrick KA, Podesta GP, Evans R. Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. *Journal of Geophysical Research: Oceans*. 2001 May 15; 106(C5):9179–97.
72. Gove JM, McManus MA, Neuheimer AB, Polovina JJ, Drazen JC, Smith CR, et al. Near-island biological hotspots in barren ocean basins. *Nature communications*. 2016 Feb 16; 7:10581. <https://doi.org/10.1038/ncomms10581> PMID: 26881874
73. Chassot E, Bonhommeau S, Dulvy NK, Mélin F, Watson R, Gascuel D, et al. Global marine primary production constrains fisheries catches. *Ecology letters*. 2010 Apr 1; 13(4):495–505. <https://doi.org/10.1111/j.1461-0248.2010.01443.x> PMID: 20141525
74. Duarte CM, Cebrian J. The fate of marine autotrophic production. *Limnology and Oceanography*. 1996 Dec 1; 41(8):1758–66.
75. Boss E, Zaneveld JR. The effect of bottom substrate on inherent optical properties: evidence of biogeochemical processes. *Limnology and Oceanography*. 2003 Jan 1; 48(1part2):346–54.
76. Bejarano S, Jouffray JB, Chollett I, Allen R, Roff G, Marshall A, et al. The shape of success in a turbulent world: Wave exposure filtering of coral reef herbivory. *Functional Ecology*. 2017 Feb 1.
77. Li N, Cheung KF, Stopa JE, Hsiao F, Chen YL, Vega L, et al. Thirty-four years of Hawaii wave hindcast from downscaling of climate forecast system reanalysis. *Ocean Modelling*. 2016 Apr 30; 100:78–95.
78. Done TJ. Coral community adaptability to environmental change at the scales of regions, reefs and reef zones. *American Zoologist*. 1999 Feb 1; 39(1):66–79.
79. Kleypas JA, McManus JW, Meñez LA. Environmental limits to coral reef development: where do we draw the line?. *American Zoologist*. 1999 Feb 1; 39(1):146–59.
80. Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg OV. Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology*. 2005 Dec 1; 11(12):2251–65.
81. Heron SF, Liu G, Rauenzahn JL, Christensen TR, Skirving WJ, Burgess TF, et al. Improvements to and continuity of operational global thermal stress monitoring for coral bleaching. *Journal of Operational Oceanography*. 2014 Aug 1; 7(2):3–11.
82. Stamoulis KA, Delevaux JM. Data requirements and tools to operationalize marine spatial planning in the United States. *Ocean & Coastal Management*. 2015 Nov 30; 116:214–23.
83. Cinner JE, Huchery C, MacNeil MA, Graham NA, McClanahan TR, Maina J, et al. Bright spots among the world’s coral reefs. *Nature*. 2016 Jul 21; 535(7612):416–9. <https://doi.org/10.1038/nature18607> PMID: 27309809
84. Stamoulis KA, Poti M, Delevaux JMS, Donovan MK, Friedlander AM, and Kendall MS. Chapter 4: Fishes—Reef Fish. pp. 156–196. In: B.M. Costa and M.S. Kendall (eds.), *Marine Biogeographic Assessment of the Main Hawaiian Islands*. Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration. OCS Study BOEM 2016–035 and NOAA Technical Memorandum NOS NCCOS 2016.214. 359 pp.
85. Friedlander A, Nowlis JS, Sanchez JA, Appeldoorn R, Usseglio P, McCormick C, et al. Designing effective marine protected areas in Seaflower Biosphere Reserve, Colombia, based on biological and sociological information. *Conservation Biology*. 2003 Dec 1; 17(6):1769–84.



86. Stamoulis KA, Friedlander AM. A seascape approach to investigating fish spillover across a marine protected area boundary in Hawai'i. *Fisheries Research*. 2013 Jul 31; 144:2–14.
87. Friedlander AM, Stamoulis KA, Kittinger JN, Drazen JC, Tissot BN. Understanding the scale of Marine protection in Hawai'i: from community-based management to the remote Northwestern Hawaiian Islands. *Mar. Manag. Areas Fish*. 2014 Oct 27; 69:153.
88. Rassweiler A, Costello C, Hilborn R, Siegel DA. Integrating scientific guidance into marine spatial planning. *Proceedings of the Royal Society of London B: Biological Sciences*. 2014 Apr 22; 281(1781):20132252.
89. Wiegner TN, Tubal RL, MacKenzie RA. Bioavailability and export of dissolved organic matter from a tropical river during base-and stormflow conditions. *Limnology and Oceanography*. 2009 Jul 1; 54(4):1233–42.
90. Oleson KL, Falinski KA, Lecky J, Rowe C, Kappel CV, Selkoe KA, et al. Upstream solutions to coral reef conservation: The payoffs of smart and cooperative decision-making. *Journal of environmental management*. 2017 Apr 15; 191:8–18. <https://doi.org/10.1016/j.jenvman.2016.12.067> PMID: 28082251
91. Storlazzi CD, Field ME, Bothner MH, Presto MK, Draut AE. Sedimentation processes in a coral reef embayment: Hanalei Bay, Kauai. *Marine Geology*. 2009 Aug 15; 264(3):140–51.
92. Stender Y, Jokiel PL, Rodgers KS. Thirty years of coral reef change in relation to coastal construction and increased sedimentation at Pelekane Bay, Hawai'i. *PeerJ*. 2014 Mar 13; 2:e300. <https://doi.org/10.7717/peerj.300> PMID: 24688875
93. Izuka SK, Abbott LL. Streamflow, suspended-sediment, and soil-erosion data from Kaulana and Hakioawa watersheds, Kaho'olawe, Hawai'i. *US Geological Survey*; 2010.
94. Rooney JJ, Wessel P, Hoeke R, Weiss J, Baker J, Parrish F, et al. Geology and geomorphology of coral reefs in the Northwestern Hawaiian Islands. *Coral Reefs of the USA*. 2008:519–71.
95. Dollar SJ, Tribble GW. Recurrent storm disturbance and recovery: a long-term study of coral communities in Hawaii. *Coral Reefs*. 1993 Nov 1; 12(3–4):223–33.
96. Friedlander AM, Brown EK, Jokiel PL, Smith WR, Rodgers KS. Effects of habitat, wave exposure, and marine protected area status on coral reef fish assemblages in the Hawaiian archipelago. *Coral Reefs*. 2003 Oct 1; 22(3):291–305.
97. Storlazzi CD, Ogston AS, Bothner MH, Field ME, Presto MK. Wave-and tidally-driven flow and sediment flux across a fringing coral reef: Southern Molokai, Hawaii. *Continental Shelf Research*. 2004 Aug 31; 24(12):1397–419.
98. McClanahan TR, Maina J, Moothien-Pillay R, Baker AC. Effects of geography, taxa, water flow, and temperature variation on coral bleaching intensity in Mauritius. *Marine Ecology Progress Series*. 2005 Aug 15; 298:131–42.
99. Anderson DM, Glibert PM, Burkholder JM. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*. 2002 Aug 1; 25(4):704–26.
100. Friedlander AM, Brown EK, Monaco ME. Coupling ecology and GIS to evaluate efficacy of marine protected areas in Hawaii. *Ecological Applications*. 2007 Apr 1; 17(3):715–30. PMID: 17494391
101. Olsen E, Kleiven AR, Skjoldal HR, von Quillfeldt CH. Place-based management at different spatial scales. *Journal of coastal conservation*. 2011 Jun 1; 15(2):257–69.
102. Norse EA, Crowder LB, Gjerde K, Hyrenbach D, Roberts C, Safina C, Soule ME. Place-based ecosystem management in the open ocean. *Marine conservation biology: The science of maintaining the sea's biodiversity*. 2005 May 9:302–27.
103. Norse EA. Ecosystem-based spatial planning and management of marine fisheries: why and how?. *Bulletin of Marine Science*. 2010 Apr 1; 86(2):179–95.
104. Kittinger JN, Koehn JZ, Le Cornu E, Ban NC, Gopnik M, Armsby M, et al. A practical approach for putting people in ecosystem-based ocean planning. *Frontiers in Ecology and the Environment*. 2014 Oct 1; 12(8):448–56.
105. Lorenzen K, Steneck RS, Warner RR, Parma AM, Coleman FC, Leber KM. The spatial dimensions of fisheries: putting it all in place. *Bulletin of Marine Science*. 2010 Apr 1; 86(2):169–77.
106. Douvère F. The importance of marine spatial planning in advancing ecosystem-based sea use management. *Marine policy*. 2008 Sep 30; 32(5):762–71.
107. Shackeroff JM, Hazen EL, Crowder LB. The oceans as peopled seascapes. *Ecosystem-based management for the oceans*. 2009:33–54.
108. Le Cornu E, Kittinger JN, Koehn JZ, Finkbeiner EM, Crowder LB. Current practice and future prospects for social data in coastal and ocean planning. *Conservation biology*. 2014 Aug 1; 28(4):902–11. <https://doi.org/10.1111/cobi.12310> PMID: 24779578

109. Cash DW, Borck JC, Patt AG. Countering the loading-dock approach to linking science and decision making: comparative analysis of El Niño/Southern Oscillation (ENSO) forecasting systems. *Science, technology, & human values*. 2006 Jul; 31(4):465–94.
110. Lester SE, Costello C, Halpern BS, Gaines SD, White C, Barth JA. Evaluating tradeoffs among ecosystem services to inform marine spatial planning. *Marine Policy*. 2013 Mar 31; 38:80–9.
111. White C, Halpern BS, Kappel CV. Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proceedings of the National Academy of Sciences*. 2012 Mar 20; 109(12):4696–701
112. Berkes F. Evolution of co-management: role of knowledge generation, bridging organizations and social learning. *Journal of environmental management*. 2009 Apr 30; 90(5):1692–702. <https://doi.org/10.1016/j.jenvman.2008.12.001> PMID: 19110363
113. Armitage D, Berkes F, Dale A, Kocho-Schellenberg E, Patton E. Co-management and the co-production of knowledge: learning to adapt in Canada's Arctic. *Global Environmental Change*. 2011 Aug 31; 21(3):995–1004.
114. Bremer LL, Delevaux JM, Leary JJ, Cox LJ, Oleson KL. Opportunities and Strategies to Incorporate Ecosystem Services Knowledge and Decision Support Tools into Planning and Decision Making in Hawai'i. *Environmental management*. 2015 Apr 1; 55(4):884–99. <https://doi.org/10.1007/s00267-014-0426-4> PMID: 25651801
115. Carrier SD, Bruland GL, Cox LJ, Lepczyk CA. The perceptions of coastal resource managers in Hawai'i: The current situation and outlook for the future. *Ocean & coastal management*. 2012 Dec 31; 69:291–8.